

École polytechnique de Louvain

Energy self-sufficiency in countries with limited renewable potential

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Abstract

Achieving net-zero emissions requires radical changes in the energy and industrial system of countries at a global scale. For some countries this goal is particularly challenging due to the limited availability of renewable resources, compared to their demand for energy. Recent literature identified Belgium, South Korea, Japan, and Trinidad and Tobago among the main countries expected to experience a deficit in energy supply from domestic renewable resources. This work builds on top of recent findings, by including a larger number of resources for renewable supply, and by adopting a higher resolution when required by the small size of the countries considered. The results of this analysis indicate that Belgium will not be able to fulfill its demand, while Japan, South Korea, and Trinidad and Tobago will heavily depend on their offshore wind potential to meet their electricity demand by 2050. In a scenario where wind offshore is not intensely deployed, none of these countries will be self-sufficient and will, consequently, depend on imports to manage their energy deficit. As a summary, this study highlights how offshore wind and importing energy are crucial for these four countries to achieve self-sufficiency.

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Chapter 1

Introduction

1.1 Energy transition to reach a net-zero emissions in 2050

In the pursuit of a sustainable and environmentally responsible future, the global community is working towards the ambitious target of achieving net-zero emissions by 2050. This goal represents a significant shift in the way countries produce and consume energy, and recognizes the urgent need to curb greenhouse gas (GHG) emissions to mitigate the effects of climate change. The International Energy Agency (IEA) underscores the need for a comprehensive transformation of energy systems, which is crucial to limiting global temperature rise above 1.5°C (IEA, 2021). The document sets out a strategic roadmap outlining the key actions and milestones needed to transition from a fossil fuel-based economy to one powered predominantly by renewable sources such as solar and wind.

The Net Zero Emissions scenario (NZE), projected by IEA, envisions a substantial reduction of almost 40% in global energy-related and industrial process CO₂ emissions from 2020 to 2030. It also aims to ensure universal access to sustainable energy by 2030, coupled with a 75% reduction in methane emissions from fossil fuel use by the same year. To do so, a significant change has to be made in the energy sector, which is illustrated in Figure 1.1 showing the projected worldwide demand by 2050.

Figure 1.1: Worldwide energy demand projected by 2050.

	Energy demand (EJ)					Shares (%)		
	2019	2020	2030	2040	2050	2020	2030	2050
Total final consumption	435	412	394	363	344	100	100	100
Electricity	82	81	103	140	169	20	26	49
Liquid fuels	175	158	143	96	66	38	36	19
Biofuels	4	3	12	14	15	1	3	4
Ammonia	-	-	1	3	5	-	0	1
Synthetic oil	-	-	0	2	5	-	0	1
Oil	171	154	129	77	42	37	33	12
Gaseous fuels	70	68	68	60	53	16	17	15
Biomethane	0	0	2	5	8	0	1	2
Hydrogen	0	0	6	12	20	0	2	6
Synthetic methane	-	-	0	1	4	-	0	1
Natural gas	70	67	58	40	20	16	15	6
Solid fuels	92	89	61	46	35	22	16	10
Biomass	39	39	24	25	25	9	6	7
Coal	53	50	38	21	10	12	10	3
Heat	13	13	12	9	6	3	3	2
Other	3	3	7	11	15	1	2	4

Projected worldwide demand in order to achieve a net-zero emissions scenario by 2050. Sectors comprising Total Final Consumption (TFC) include industry (energy use and feedstock), transport, buildings (residential, services and non-specified other) and other (agriculture and other non-energy use).

Electricity demand increases by more than two times, with emerging market and developing economies contributing to over 85% of this growth. Solar PV and wind are projected to become the primary sources of global electricity before 2030, by contributing for nearly 70% of global generation by 2050. Traditional bioenergy usage is expected to be phased out by 2030. Fossil fuel demand significantly decreases by 2050: coal by 90%, oil by 75%, and natural gas by 55%. Remaining fossil fuels are used mainly in non-energy products, plants with carbon capture, and sectors lacking low-emission alternatives. Half of the emission reductions by 2030 come from energy efficiency, wind, and solar energy efficiency. Post-2030, the focus shifts to electrification, hydrogen use, and carbon capture, targeting 1.9 Gt of CO₂ removal and significant low-carbon hydrogen demand by 2050.

The net-zero emissions strategy from IEA aims for a comprehensive decarbonization of the energy sector, but faces uncertainties. Challenges like limited behavioral changes, bioenergy availability,

or carbon capture, utilisation and storage (CCUS) deployment could hinder achieving net-zero emissions by 2050. In the discourse surrounding net-zero emissions targets, divergent viewpoints have emerged regarding the feasibility and economic implications of relying solely on wind, water (hydropower), and solar energy, collectively referred to as the WWS system. Some researchers are proponents of this approach, advocating for the exclusive use of these renewable sources (Jacobson et al., 2017). In contrast, others argue that a system reliant solely on WWS would incur excessive costs, with the economic burden disproportionately impacting consumers (Clack et al., 2017).

An alternative perspective is offered, which includes biomass as a viable supplementary resource. Biomass can serve as a primary energy source for producing low-carbon molecules, such as hydrogen, or for generating more advanced energy carriers derived from it. This inclusion of biomass in the energy mix presents a potentially more economically balanced approach to achieving net-zero emissions targets, suggesting a need for a broader consideration of diverse energy sources in the transition to renewable energy (Yang et al., 2022).

Having that in mind, it is important for countries to analyze their technical potential to fulfill their demand since that can vary a lot from country to country. Recent literature highlighted that some nations might be constrained in terms of land availability for the installation of sufficient photovoltaic panels or wind turbines to satisfy their national energy demand (Tonelli et al., 2023).

These countries include Belgium, South Korea, Japan, and Trinidad and Tobago, which present restricted land for the installation of primary renewable energy plants and may face different challenges in achieving a net-zero emissions scenario. A critical aspect of research in this domain involves assessing the capability of these countries to be self-sufficient in energy production under these constraints. If self-sufficiency is not feasible, it becomes imperative to explore alternative strategies, including the import of low-carbon energy carriers, to meet their energy requirements. Building on global scale findings, our analysis focuses on a detailed description of the energy demand and potential of the four main countries that cannot reach self-sufficiency by 2050. The scope of this work is to expand the analysis from (Tonelli et al., 2023) to a wider number of primary energy sources. While (Tonelli et al., 2023) provided conclusions at the global scale, we focus on the countries that have been identified as critical in terms of availability of renewable resources, to derive a better understanding of the challenges that they face, and how they can overcome them.

1.2 National energy plans of the BEKOJAT

In order to facilitate discussion, we have created the acronym BEKOJAT to indicate the four countries considered in this study: Belgium, South Korea, Japan, and Trinidad and Tobago. Although every country has a specific energy system, these four countries are characterized by a common potential deficit in inland renewable potential compared to their energy demand.

1.2.1 Belgium

Belgium, in its pursuit of a low-carbon economy, has outlined an energy transition plan described in the 2022 Energy Policy Review by the IEA (IEA, 2022). This review shows that the country is facing a difficult situation by trying to phase out its nuclear plants and depend less on fossil fuels, while making sure that its energy supply is stable.

While notable progress has been made in expanding renewable energy, particularly in wind and solar PV sectors, the prevalent predominance of fossil fuels, comprising 71% of the energy supply in 2020, remains a significant hurdle. The need for more aggressive policies is underscored by limited reductions in GHG emissions in recent years, coupled with the nuclear phaseout by 2025 that threatens the electricity supply of the country.

Belgium has set diverse energy and climate objectives for 2030 with the goal of facilitating an energy transition and meeting the targets established by the European Union (EU). GHG emissions from the country's energy-intensive industrial facilities and significant electricity generation plants are subject to regulation through the EU Emissions Trading System (ETS). Belgium's National Energy and Climate Plan (NECP) outlines targets for 2030, including a 35% reduction in non-ETS GHG emissions compared to 2005 levels. The plan aims for primary energy demand to be below 42.7 million tonnes of oil equivalent (Mtoe), a decrease from 49.1 Mtoe in 2019 and 43.9 Mtoe in 2020. Final energy demand is targeted to be less than 35.2 Mtoe, down from 35.8 Mtoe in 2019 and 33.3 Mtoe in 2020. Additionally, the plan sets specific renewable energy goals, aiming for 17.5% of gross final energy consumption, 37.4% of electricity generation, 11.3% of heating and cooling demand, and 23.7% of transport demand. Furthermore, the plan calls for an increase in total research, development, and demonstration (RD&D) spending at least 3% of the gross domestic product (GDP). With the EU raising the 2030 GHG reduction target to 55%, Belgium must revise its goals accordingly. The NECP requires updating, incorporating heightened targets and additional measures to align with the EU's 55% reduction goal. Belgium, endorsing EU carbon neutrality by 2050, has adopted its Long-term Strategy for energy and climate (LTS2050). While LTS2050 supports the Paris Agreement and EU carbon neutrality, it lacks a clear commitment to national climate neutrality by 2050, necessitating an update to include such a commitment and a defined path.

The NECP serves as Belgium's primary energy and climate policy, outlining measures to achieve its 2030 targets. The focus is on reducing energy demand and increasing renewable energy deployment, particularly in electricity generation and transport. Offshore wind development, including the establishment of dedicated zones and competitive bidding, plays a key role. Renewable energy in transport is promoted through a federal biofuels blending mandate, while reductions in transport emissions involve vehicle taxation incentives and modal shifts. Regional responsibilities include building emissions reduction, energy efficiency, and renewable heating and cooling, with various measures such as financial support and building codes. Industry emissions and energy demand reductions are driven by the Emissions Trading System (ETS) and voluntary agreements, with a growing focus on small and medium-sized enterprises (SMEs). The government explores carbon pricing options, commits to eliminating fossil fuel subsidies, and plans tax reforms aligned with climate goals. Social tariffs and additional programs address energy poverty and ensure energy access for qualifying consumers.

Belgium emphasizes electrification as a core element of its energy transition, but challenges arise due to low heating oil and gas prices coupled with high electricity costs. Despite the efficiency and environmental benefits of electric heating, its price is 50% higher than that of natural gas or fuel oil. The elevated electricity prices result from non-generation-related charges, hindering its competitiveness and impeding investment in electrification across sectors like building heating, transport, and industrial processes. Revising the tariff structure is crucial to align electricity prices with energy transition goals, benefiting vulnerable households and enhancing industrial competi-

tiveness. Although Belgium exhibited the highest consumer switching rate for electricity in Europe in 2019, the market remains dominated by a few entities, requiring efforts to remove barriers and foster competition. Concerns also revolve around permit delays for transmission and generation infrastructure projects, particularly for onshore wind and large-scale solar PV, posing challenges to meeting energy transition goals and ensuring a secure electricity supply after the nuclear phase-out. While infrastructure projects support gas supply security after the Groningen phase-out, Belgium lacks a national strategy for decarbonizing the gas sector, necessitating clarity on mid- to long-term targets for low-carbon gases like biomethane and hydrogen, especially in anticipation of increased gas-fired electricity plant deployment following the nuclear phase-out.

1.2.2 Japan

The Japanese government developed the Strategic Energy Plan (METI, 2021) to outline the trajectory of the country's energy policy in accordance with the Basic Act on Energy Policy.

In October 2021, the Cabinet gave its approval to the Sixth Strategic Energy Plan following extensive discussions within the Advisory Committee for Natural Resources and Energy. This decision takes into account the diverse challenges confronting Japan's energy supply and demand dynamics, as well as the shifts in the global energy landscape since the formulation of the Fifth Strategic Energy Plan in 2018. The plan adopts the S+3E perspective, which means first and foremost ensuring stable supply and realizing low-cost energy supply by enhancing its efficiency on the premise of safety while making maximum efforts to pursue environmental suitability.

The formulation of the Sixth Strategic Energy Plan revolves around two primary objectives:

- Attaining carbon neutrality by 2050 and meeting the targeted reduction in greenhouse gas emissions.
- Securing a stable energy supply, minimizing costs, and concurrently addressing the challenges posed by climate change.

Under this plan, the power supply composition for 2030 is projected as follows:

- 36-38% from renewable energy (solar 14-16%; wind 5%; geothermal 1%; hydropower 11%; biomass 5%)
- 20-22% from nuclear energy
- 20% from LNG (Liquefied Natural Gas)
- 19% from coal
- 2% from oil
- 1% from hydrogen

If this energy supply and demand outlook is realized, then energy-related CO₂ will be reduced by approximately 45% compared to levels in 2013.

1.2.3 South Korea

The Ministry of Trade, Industry and Energy of South Korea released, in 2019, the “Third Energy Master Plan” (MOTIE, 2019), which focuses on a comprehensive strategy for energy transition in South Korea. There’s a significant emphasis on improving energy efficiency to reduce energy consumption by 18.6% below the Business as Usual (BaU) level by 2040, particularly in industry, buildings, and transportation sectors, translating to a reduction of 455.89 TWh/y and saving about 10.01 million € in energy imports. The plan also involves innovating the energy consumption structure by incorporating advanced technologies like the Internet of Things (IoT) and smart meters and facilitating new business models in energy management.

The document highlights a shift towards renewable energy, with a target of 30-35% renewable energy generation by 2040. Furthermore, it aims to increase the share of distributed generation from 12% in 2017 to 30% by 2040. It also discusses reducing reliance on nuclear and coal power. In terms of transport, South Korea plans to distribute 8.3 million electric vehicles and 2.9 million hydrogen vehicles by 2040. The fuel efficiency of passenger vehicles is expected to improve about 2 times in 2040, and heavy-duty vehicles’ fuel efficiency is expected to improve about 1.5 times.

The roadmap outlines ambitious targets for the hydrogen industry, aiming to dramatically expand hydrogen usage and establish a comprehensive value chain encompassing production, storage, transport, and utilization. By 2040, the plan targets a supply of 5.26 million tons of hydrogen in comparison to the 130,000 tons produced in 2018. The plan outlines a phased approach to developing the hydrogen industry, with phases focusing on ecosystem development, expansion of hydrogen usage, and leading the global hydrogen economy. This includes accelerating hydrogen generation and establishing large-scale supply and demand systems, with a focus on a carbon-free supply chain.

1.2.4 Trinidad and Tobago

The government of Trinidad and Tobago is currently developing a national energy policy green paper that recognizes renewable energy combined with energy efficiency and utilization of compressed natural gas in the transportation sector as important strategies for the promotion of sustainable development of the nation. Therefore, without a national energy plan, in this work, we will evaluate a suggested energy transition policy for the country (Jupiter and van Meurs, 2021). The article utilizes the IEA’s Net-Zero by 2050 scenario and serves as an initiative to address the significant impact of international climate change policies on Trinidad and Tobago’s economy, which is heavily reliant on exports of LNG, ammonia, methanol, and fertilizers. It also recommends adopting the year 2060 as the target for Trinidad and Tobago to achieve Net-Zero Carbon emissions.

The country’s natural gas reserves were reported at 10.7 Tcf (equivalent to 3262.453 TWh) in 2020, with a predicted decline in production by about 10% per year, leading to approximately 200 MMcf/day (equivalent to 60.98 TWh) by 2050. The country’s proven crude oil reserves stand at 220 million barrels, with production expected to decline by 6.5% per year, resulting in 7,500 barrels of oil per day (bopd) by 2050. The overall strategy for oil and gas development emphasized in the document focuses on maximizing the benefits from the remaining oil and gas potential while transitioning to renewable energy sources.

An important key to this transition is the restructuring of the power sector. The document (Jupiter and van Meurs, 2021) highlights the need for a transition to renewable energy, focusing on utility-

scale solar and offshore wind energy. However, the country’s electricity generation heavily relies on subsidized natural gas, making it more cost-effective than renewable sources nowadays. The electricity tariffs, unchanged since 2009, are significantly lower than international rates, further discouraging the shift to renewables. Thus, the researchers point out that, without policy changes, transitioning to renewable energy will remain uneconomical, emphasizing the need for reforms in that sense.

Additionally, it proposes transitioning other sectors like electric planes, taxis, and ferries to renewable energy sources. It also underscores that the cement industries are difficult to convert to renewable energy. It is therefore important that this industry should have priority in terms of natural gas supply relative to other sectors.

New industries might also be created by 2050. The potential of renewable hydrogen is notably prominent. Currently, the production of renewable hydrogen, achieved through water electrolysis powered by renewable energy, is not economically competitive. However, there is optimism that by 2030, the production costs could decrease to 1.81 €/kg. This reduction in cost would make renewable hydrogen a financially feasible option. The document suggests that the country could competitively produce renewable hydrogen for both local use and the broader Caribbean market.

Transitioning to a renewable ammonia industry is also a pivotal focus. Trinidad and Tobago already has a large ammonia industry, and industries that utilize ammonia derivatives, which places the country in a favorable position to transition from a gas-based to a renewable ammonia industry. The infrastructure required for both types of ammonia production, including storage and transport, is quite similar, which could facilitate this transition.

Renewable methanol production is another area to be explored in the country. While transitioning to renewable methanol presents its own set of challenges, particularly in securing large volumes of low-cost CO₂, the authors suggest prioritizing natural gas for methanol plants to prolong their operational lifespan. However, if the production of renewable methanol becomes more feasible, it could serve as an ideal fuel for marine shipping, especially considering Trinidad and Tobago’s strategic location near the Panama Canal.

These new industries are integral to Trinidad and Tobago’s strategy for moving away from a reliance on fossil fuels towards a sustainable, renewable energy-driven economy. The development of these sectors not only aligns with global renewable energy trends but also holds the promise of economic benefits and job creation, which are crucial for the country’s long-term economic growth and sustainability. However, (Jupiter and van Meurs, 2021) also warns that Trinidad and Tobago does not have a competitive advantage in producing renewable energy compared to other countries. The country would have difficulty competing with the ultra-low-cost renewable countries (Chile, Australia, Oman, etc.) for large-scale hydrogen export, due to its constrained land availability and average conditions for renewable generation. The report highlights that large-scale private investments in renewable energy are more likely to occur in countries that aggressively pursue such opportunities, implying that Trinidad and Tobago may lag behind in this aspect if it does not implement relevant policies.

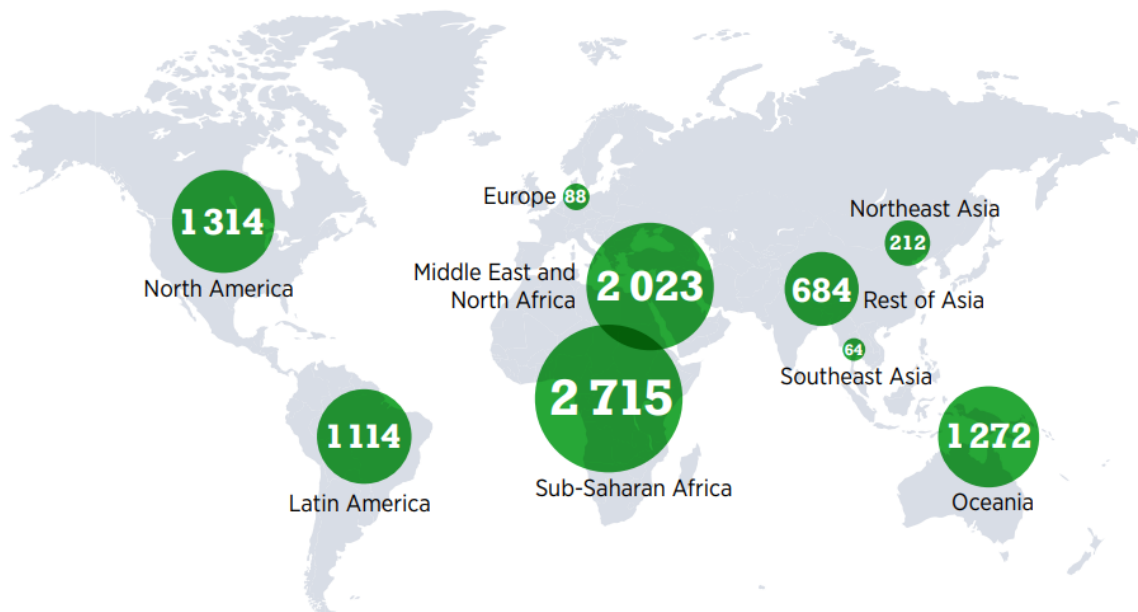
1.3 2050 main exporters

An important aspect of the strategies of countries with constrained land for energy generation is the possibility of importing energy. Cross-border energy trade plays an important role in building a net-zero emissions scenario. Integrating power systems at a regional scale can bring many benefits, such as enhancing energy security and facilitating wider access to clean and affordable electricity. Connecting power systems also means a larger range of generation capacity can be used to meet demand and maintain a stable frequency.

Furthermore, in that scenario, hydrogen is becoming a key element in economic diplomacy, with access to hydrogen often viewed as crucial for energy security and national resilience, especially in industries where other solutions are not feasible. Governments are actively forging bilateral deals and agreements to facilitate cross-border hydrogen trade, similar to the early days of the liquefied natural gas (LNG) industry. These deals include feasibility studies, memorandums of understanding, energy partnerships, and even trial shipments. Countries like Canada, Chile, Germany, Italy, Japan, and Spain have explicitly mentioned potential bilateral hydrogen trading relations in their national strategies. This is leading to new energy trade relations, shipping lanes, and trade routes.

Figure 1.2 exhibits the green hydrogen potential in the different world regions.

Figure 1.2: Technical potential for producing green hydrogen under USD 1.5/kg by 2050 (EJ/y).

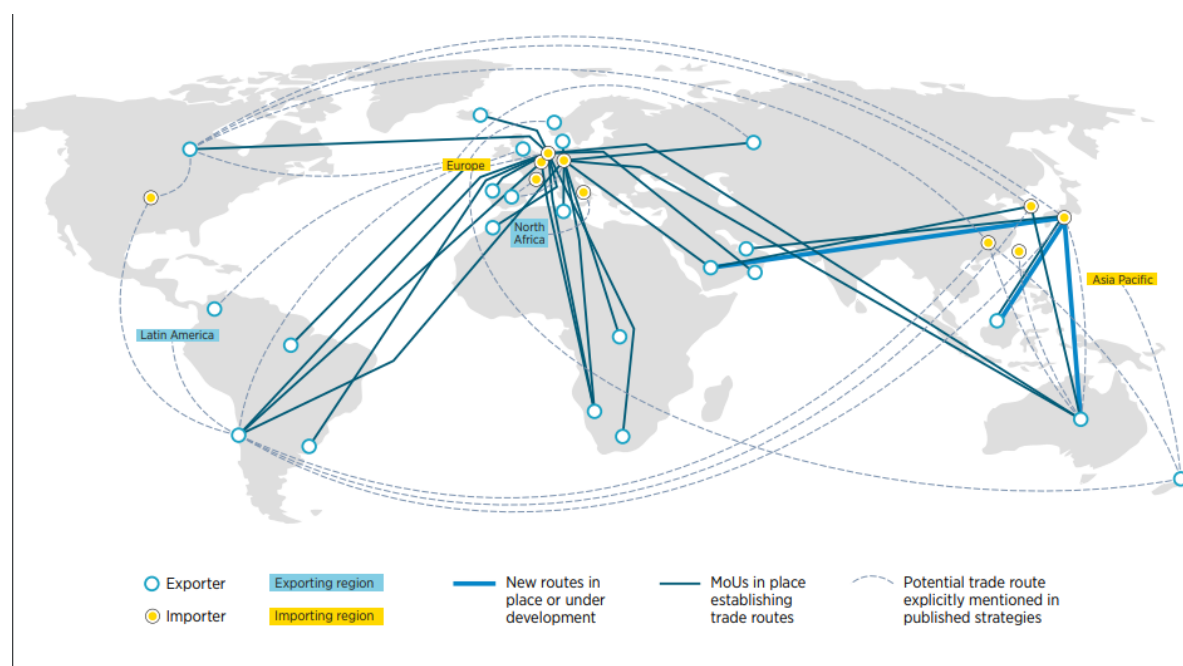


The image illustrates the global distribution of the technical potential for producing renewable hydrogen around the world in EJ (IRENA, 2019). Each region is represented by a green bubble, with the size corresponding to the magnitude of the metric. Technical potential has been calculated based on land availability considering several exclusion zones (protected areas, forests, permanent wetlands, croplands, urban areas, slope of 5% (PV) and 20% (onshore wind), population density). Water availability was not considered in the analysis.

This map helps understand what are projected to be the tendencies of renewable hydrogen production worldwide, with some regions standing out due to their large exporting potential. Countries traditionally dependent on energy imports could reverse their roles by leveraging their abundant renewable resources for renewable hydrogen production. This possible change, based on whether producing renewable hydrogen is technically and financially viable, marks a big change in worldwide energy relationships. Regions like Africa, the Americas, the Middle East, and Oceania are identified as having high technical potential for renewable hydrogen production.

Figure 1.3 highlights the expanding network of hydrogen trade routes. IRENA envisages that two-thirds of green hydrogen production in 2050 would be used locally, and one-third traded across borders. Pipelines, including adapted natural gas pipelines, are likely to facilitate half of this trade. The other half would be loaded on ships in the form of hydrogen derivatives, mainly ammonia.

Figure 1.3: An expanding network of hydrogen trade routes, plans and agreements.



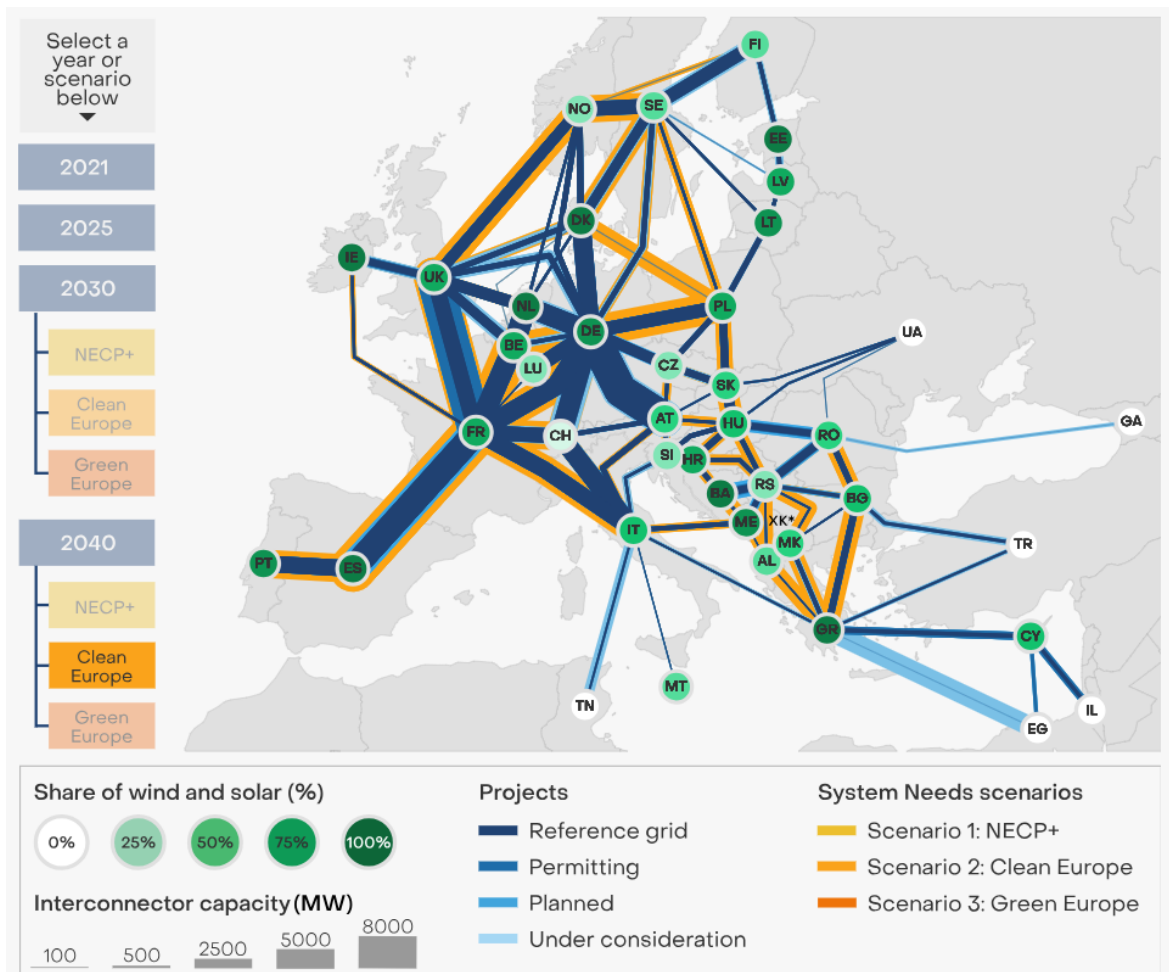
The figure depicts a global map highlighting international trade routes for hydrogen, with a focus on exporting and importing regions (IRENA, 2019). The density of the lines and the interconnections of the regions underscore the complexity and global scale of this trading system.

Europe and Asia Pacific appear as central hubs in this network, with multiple routes converging on them from various regions such as Latin America, North Africa, and others, indicating their significant role as importers in the global trade landscape. The presence of new routes under development and potential routes outlined by strategies reveals ongoing changes and expansions in global trade dynamics, reflecting economic, geopolitical, and possibly environmental considerations that drive these international relationships.

1.3.1 European interconnection

Besides hydrogen import, electricity import through interconnected grids can play an important role in guaranteeing energy sufficiency and security to countries, especially the ones with an energy deficit. Since Trinidad and Tobago and Japan are islands, and South Korea is only connected to North Korea, that type of power import is not a very viable and interesting solution in case of them not being self-sufficient and, consequently, hydrogen import should be prioritized. Hence, we will only analyze grid interconnections for Belgium and Europe. Figure 1.4 displays the evolution of Europe's interconnected power grid for a Clean Europe scenario in 2040. This scenario is based on the Technology Driven pathway from Ember's New Generation report (Rosslowe et al., 2021). It presents a least-cost pathway to zero-carbon electricity by 2050 within a Paris Agreement compatible carbon budget.

Figure 1.4: The evolution of Europe's interconnected power grid: An interactive map.



The figure displays a map of electricity interconnection in Europe under the Clean Europe scenario. The figure also shows the expected share of wind and solar per country in the region, which enables visualization of the expected main exporters of electricity (Rosslowe et al., 2021).

Table 1.1 provides a numerical display of the system needs of Belgium projected by Ember for 2040, in the Clean Europe scenario.

Table 1.1: Grid capacity between Belgium and exporting countries projected to 2040.

Border	Exporting country	Grid capacity (MW)
UK-BE	UK	3800
FR-BE	FR	5300
LU-BE	LU	1180
NL-BE	NL	5400
DE-BE	DE	2000
DK-BE	DK	0

Belgium has direct connections with five countries: the United Kingdom, France, Luxembourg, Germany, and the Netherlands. It can be seen that higher capacity is planned in the interconnection with France and the Netherlands, making them the primary candidates for Belgium’s future imports.

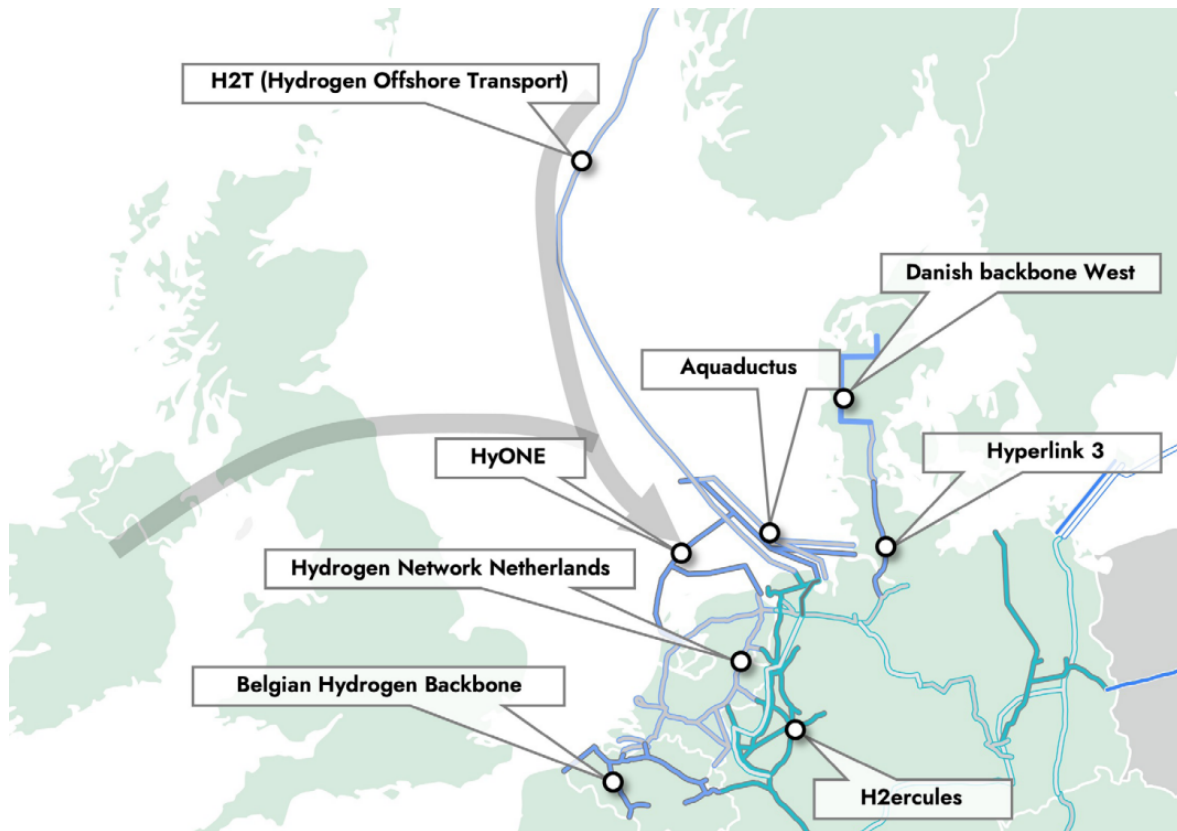
1.3.2 Hydrogen transport in Europe

It is also worth discussing the hydrogen transport network being developed in Europe. In a comprehensive energy system, both electricity and hydrogen transmission are essential. However, a report by the European Hydrogen Backbone (EHB) (EHB, 2023) indicated that pipeline systems for hydrogen, especially one utilizing retrofitted gas pipelines (Fabian Neumann, 2023), are more cost-effective compared to high-voltage direct current (HVDC) or high voltage alternating current (HVAC) options for energy transfer. Therefore, a new hydrogen network could replace the need for extensive electricity grid reinforcement (Fabian Neumann, 2023). As a result, developing hydrogen infrastructure is crucial for efficiently scaling up Europe’s renewable energy resources. This includes boosting domestic renewable hydrogen production and facilitating substantial increases in low-carbon energy transfers both within EU countries and through imports from non-EU countries.

The EHB has consistently supported the concept of European hydrogen corridors, recognizing their potential to provide an affordable and secure energy supply in Europe. These corridors economically link diverse regions with varying hydrogen production and consumption patterns, influenced by demographic, geographic, economic, and climatic differences. Some European areas, like the Nordics, Baltics, North Sea, and southern Europe, have a surplus of low-cost hydrogen resources, benefiting from abundant renewable energy sources, high-capacity factors, and ample land. Conversely, central European regions might depend on hydrogen imports from neighboring European countries or elsewhere to satisfy their hydrogen needs.

Creating cost-effective cross-border pipeline corridors that connect hydrogen-rich regions with central European consumers is becoming vital as hydrogen use grows in transportation, industry, and power sectors. Figure 1.5 displays the projects in the North Sea region planned for commissioning by EHB partners in the coming years.

Figure 1.5: Selected projects by EHB in the North Sea.



The figure displays the selected projects by EHB in the North Sea. (EHB, 2023)

The North Sea Corridor is focused on accelerating hydrogen delivery to demand centers in the western regions of Germany. A key source of hydrogen in this corridor comes from the substantial offshore wind potential in the area. The countries in this region have been making efforts to build pipelines to transport hydrogen. Additionally, projects to transport hydrogen across the mainland and into Europe are rapidly progressing, such as the Belgium Hydrogen Backbone.

1.4 Research question

The thesis aims to comprehensively analyze the energy landscape of Belgium, Japan, South Korea, and Trinidad and Tobago, focusing on their current and future demands for electricity and hydrogen. It will assess the technical potential of various renewable energy sources available within these countries, including onshore and offshore wind power, photovoltaic power, and biomass energy. A central question that the thesis seeks to address is whether these countries need to import energy from abroad.

Additionally, the thesis will identify potential neighboring or overseas countries as sources for importing energy, particularly in the form of hydrogen or derived carriers. The final aspect of the thesis involves contextualizing the findings within the framework of the existing national energy

strategies of the countries under study. This will enable the formulation of policy recommendations that align with each country's specific energy needs and goals.

Finally, our research question could be summarized as: "In a net-zero emission scenario by 2050, can these countries be self-sufficient? If not, how to fill in the gap?".

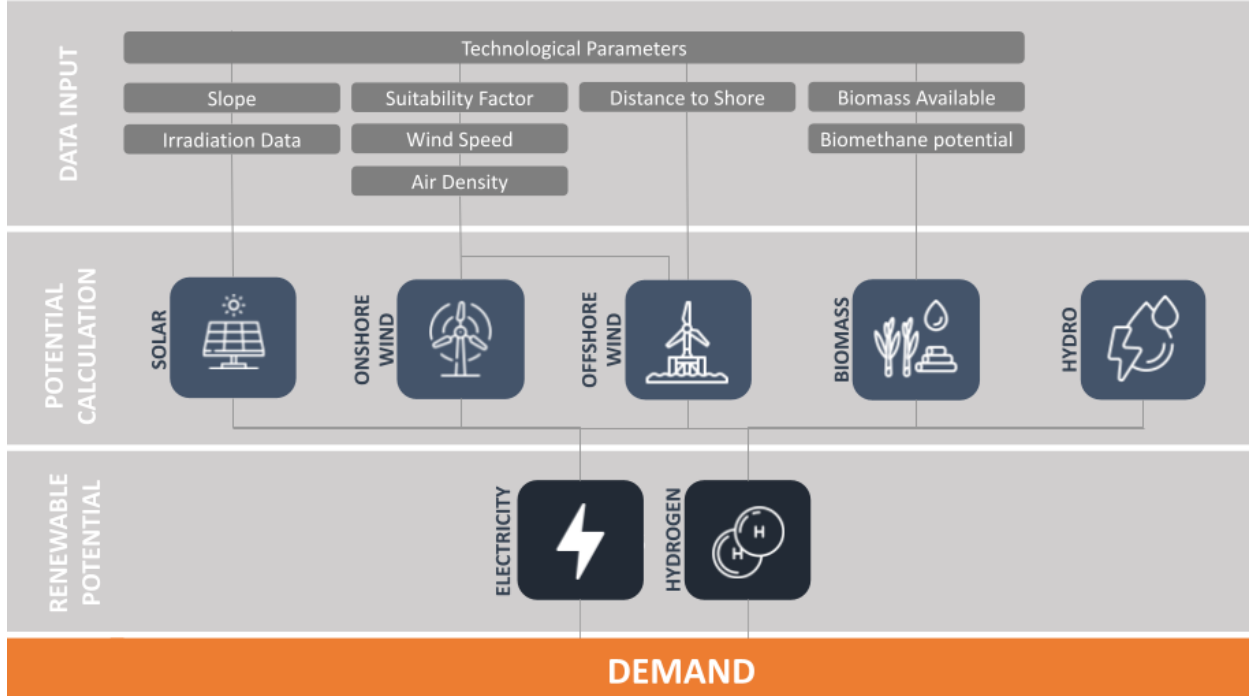
Chapter 2

Methodology

The present study starts by assessing the energy demand for each country and projecting it into a 2050 net-zero emissions scenario, while considering its particular profiles. Following that, it is necessary to assess the technical potential for electricity and hydrogen that these countries present. Different modeling scenarios and technologies have been developed in order to analyze possible pathways to a net-zero emissions energy system.

Figure 2.1 presents a simple scheme summarising our methodology.

Figure 2.1: Methodology schematic.



The figure displays a schematic of the methodology employed. Five generation technologies are considered: solar (PV or CSP), onshore wind, offshore wind, biomass, and hydropower. The first step is gathering the necessary input. This data, once gathered, serves as the foundational element in the subsequent phase of calculation. The technical potential obtained can then be used to supply the electricity and the hydrogen demand.

Furthermore, an important step in analyzing these potentials is considering the uncertainties surrounding these technologies. Some parameters, to be described below, can have different values depending on the assumptions and technologies considered. The uncertainty values used can be seen in Appendix A.1.

2.1 Projected demand for 2050

To establish the projected demand for 2050 to achieve a net-zero emissions system, an initial examination of the current demand is essential. In our study, we analyze the 2019 energy demand of each country, breaking it down by sector (i.e. by Manufacturing, construction and mining, by Transport, by Agriculture, forestry and fishing, by Buildings and by Non-energy use) and currently used energy sources (i.e. primary coal and peat, coal and peat products, primary oil, oil products, natural gas, biofuels and waste, nuclear, electricity and heat). The methodology employed to derive country-and sector-specific projections is based on the variation of demand for each sector between 2019 and the projected demand for 2050. Those variations of demand are based on global projections made by the IEA, in a report evaluating the necessary steps to achieve a net-zero emissions system by 2050 (IEA, 2021). Following that, the 2050 total energy demand for each country's sectors is allocated

among the different projected energy sources based on their respective shares, as projected by the IEA in the report. For instance, if a country has a 2050 demand of 100 TWh/y in transport and the projected demand of hydrogen in the transport sector is of 16%, then a hydrogen demand of 16 TWh/y is added to this sector demand. It is important to note that new energy sources are proposed at this point. Those projected energy sources encompass electricity, liquid fuels (biofuels, ammonia, synthetic oil, oil), gaseous fuels (biomethane, hydrogen, synthetic methane, natural gas), solid fuels (biomass, coal) and heat. To compute per capita values, we also take into account the projected demographic changes for each country in 2050 (The World Bank Group, 2023).

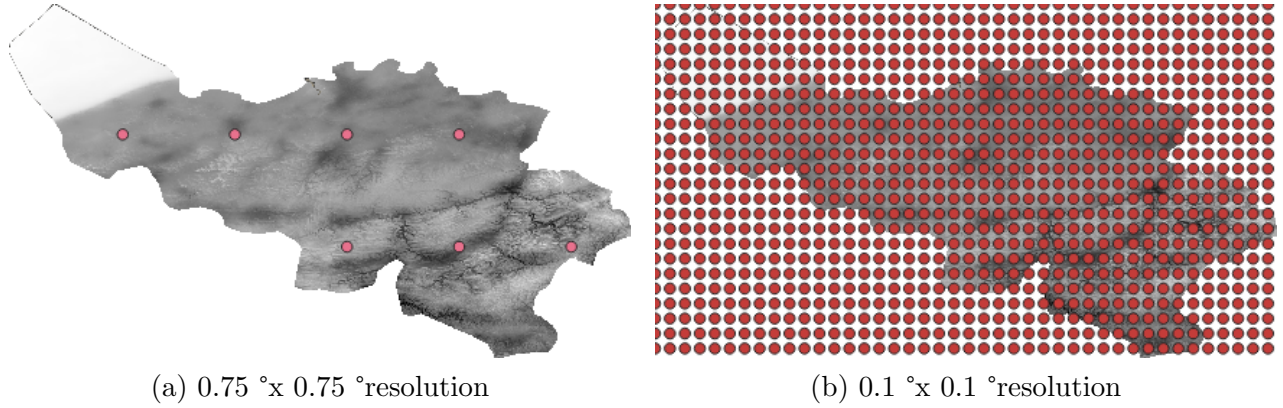
2.2 Onshore and offshore wind potential

In terms of wind, the study by Dupont et al. (Dupont et al., 2018) estimates the global potential of wind energy, taking into account both physical and economic constraints. This comprehensive approach involves assessing the theoretical wind potential across various geographic locations using a grid cell model. Each cell’s suitability for wind farm installation is evaluated based on several factors, including land cover, water depth, and proximity to shore.

2.2.1 Data resolution

In our study, instead of using a $0.75^\circ \times 0.75^\circ$ resolution, we increased the resolution of the data to a $0.1^\circ \times 0.1^\circ$ resolution. A higher resolution is necessary when analyzing countries with small inland areas and exclusive economic zones. Figure 2.2(a) highlights the size of the Economic Zone of Belgium compared to a coarse resolution. For instance, in a 0.75° analysis, no offshore point is considered for Belgium which significantly underestimates the country’s offshore potential. In comparison, in small countries, a 0.1° resolution allows the analysis of the potential even within a small economic zone, such as for Belgium. Small countries often have diverse land use patterns within confined areas. A finer resolution allows for a more detailed examination of available land for renewable energy projects, considering constraints such as agricultural land, urban areas, and conservation zones.

Figure 2.2: Resolution comparison.



The figure shows two different data resolutions displayed over Belgium: 0.75 °x 0.75°(a) and 0.1°x 0.1°(b).

2.2.2 Wind technologies

Wind energy, harnessed through various technologies, has become important in the global shift towards renewable energy sources. There are two primary forms of wind energy exploitation: onshore and offshore wind technologies, each with distinct characteristics and technological advancements.

Onshore wind technology refers to inland wind turbines. These turbines are usually installed in areas with consistent wind patterns, such as hilltops, open plains, or near coastlines where wind flow is unimpeded by topographical obstructions. The technology has significantly evolved over the years, with improvements in turbine design, materials, and control systems. Onshore turbines are generally easier and less expensive to install and maintain compared to their offshore counterparts, mainly due to their accessibility. However, onshore wind farms often face constraints such as limited land availability and environmental impact concerns. The efficiency of these farms is subject to variations in wind speed and land topography, making site selection a critical aspect of their development.

Offshore wind technology involves turbines installed in bodies of water, usually in seas or lakes. This technology capitalizes on the higher and more consistent wind speeds found over water and the reduced visual and noise impact compared to onshore installations. Offshore turbines are typically larger and more powerful than onshore units, generating more electricity per turbine. Technological advancements in offshore wind have led to the development of floating platforms, which allow turbines to be deployed in deeper waters where winds are steadier and less turbulent. However, offshore wind technology presents substantial challenges, including higher installation and maintenance costs, logistical complexities, and the need for robust designs to withstand harsh marine environments. Additionally, there are concerns regarding the impact on marine ecosystems and the need for extensive undersea cabling to transmit electricity back to land.

2.2.3 Wind Data

The wind speed data is obtained from the Global Wind Atlas at a height of 100 m (Global Wind Atlas, 2023). The dataset offers a wind resource mapping at 250 m horizontal spacing.

Table 2.1 has the main data parameters defined for the computation.

Table 2.1: Main wind parameters.

Parameter	Value	Unit
Cut-in speed	3	m/s
Cut-out speed	25	m/s
Maximum power coefficient of onshore turbine	50	%
Time wind onshore turbine is not shut down	97	%
Time wind offshore turbine is not shut down	95	%
Wind lifetime	25	y
Wh to Joule	3600	J/Wh

2.2.4 Area available for wind production

The available area for wind generation on each cell depends on its respective suitability factor since many areas are not suitable for wind farm installation. This factor is applied to each grid cell with a keen focus on geographical constraints. In onshore areas, this factor is closely tied to the type of land cover, as different terrains can significantly impact the feasibility of establishing wind farms, as can be seen in A.3. This results in a calculated suitability factor assigned to each grid cell, defined as the cell's fraction suitable for wind farm installation.

For offshore wind farms, the suitability factor is confined to exclusive economic zones, extending up to 200 nautical miles from the coast. Here, the potential of wind energy is influenced by the distance to the shore. There are environmental and visual impact considerations since turbines too close to shore are more likely to affect coastal ecosystems and are more visible, increasing visual impact concerns from coastal communities and tourism. On the other hand, as the distance from the shore increases, the complexity and cost of constructing and maintaining wind turbines also rise. These challenges include the transportation of large turbine components, the installation process which becomes more complicated in deeper waters, and the need for more robust structures to withstand harsher oceanic conditions. Not only the generation but also the transmission becomes increasingly more challenging with the distance.

The following table was developed based on the National Renewable Energy Laboratory (NREL) evaluation (NREL, 2015).

Table 2.2: Local suitability factors based on distance and conditions for the reference case.

Distance/Condition	Local Suitability Factor
0 - 10 km	10%
10km - 37 km	33%
37 km - 160 km	67%
>160 km	0

Figure 2.3 describes the involved parameters to compute the available area for wind power generation (onshore and offshore).

Figure 2.3: Available area for wind calculation.



Parameters involved in the calculation of the available area for wind.

The area of one grid cell (a_{cell}) is formulated in the methodology as:

$$a_{cell} = 2\pi \cdot R^2 \cdot \left| \sin \left(\left(\text{Lat} + \frac{\text{resol}}{2} \right) \cdot \frac{\pi}{180} \right) - \sin \left(\left(\text{Lat} - \frac{\text{resol}}{2} \right) \cdot \frac{\pi}{180} \right) \right| \cdot \frac{\text{resol}}{360} \quad (m^2) \quad (2.1)$$

where:

- R is the Earth radius (m)
- Lat is latitude (°)
- resol is resolution (°)

After assigning each cell to an onshore and offshore suitability factor, the area available for onshore generation ($A_{onshore}$) and the area available for wind offshore generation ($A_{offshore}$) is given as follows:

$$\begin{aligned} A_{onshore} &= a_{cell} \cdot sf_{wind}^{onshore} \quad (m^2) \\ A_{offshore} &= a_{cell} \cdot sf_{wind}^{offshore} \quad (m^2) \end{aligned}$$

where:

- $sf_{wind}^{onshore}$ is the suitability factor for wind onshore generation in one cell in (%)
- $sf_{wind}^{offshore}$ is the suitability factor for wind offshore generation in one cell in (%)

2.2.5 Wind potential computation

The methodology used for calculating the wind potential is based on the Weibull parameters. The calculation of wind energy potential utilizing Weibull parameters, denoted as c (scale parameter) and k (shape parameter), is a fundamental aspect in renewable energy studies. The Weibull distribution is favored for its ability to accurately represent various wind speed distributions.

The probability density function (PDF) of the Weibull distribution is a critical component, defined as:

$$f(v; c, k) = \frac{k}{c} \left(\frac{v}{c}\right)^{k-1} e^{-(v/c)^k} \quad (2.2)$$

where:

- c is the scale parameter
- k is the shape parameter
- v is wind speed (m/s)

The Weibull parameters c and k are empirically determined from site-specific wind speed data. Statistical methods such as the method of moments or maximum likelihood estimation are typically used for this estimation. It is possible to calculate the parameters with:

$$k = \left(\frac{\sigma}{\mu}\right)^{-1.086} \quad (2.3)$$

where:

- σ represents the standard deviation of the wind speed in (m/s).
- μ represents the mean wind speed in (m/s)

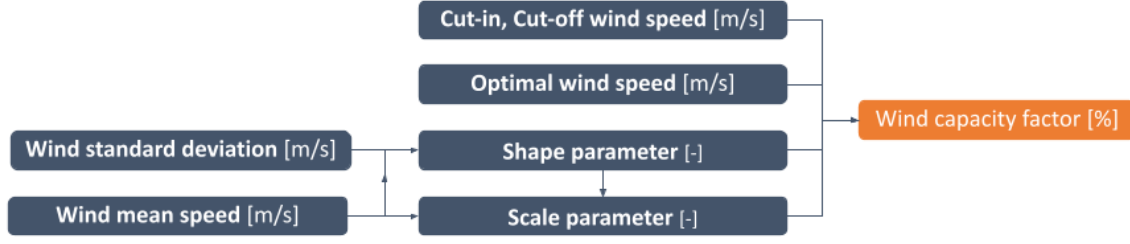
$$c = \mu \left[\Gamma \left(1 + \frac{1}{k} \right) \right]^{-1} \quad (2.4)$$

where:

- Γ represents the gamma function.

Once both c and k are obtained, the wind capacity factor can be computed, which is essentially the ratio of the energy produced by a turbine over a period of time to the energy it would have produced if operating continuously at its nominal power. Figure 2.4 shows the parameters involved in this calculation.

Figure 2.4: Wind capacity factor calculation.



Parameters involved in the calculation of wind capacity factor. The shape parameter and the scale parameter also depend on other variables, which are the wind standard deviation and the wind mean speed.

Therefore, the wind capacity factor (C_{wind}) is obtained through the equation below. The capacity factor varies significantly with the location of the grid cell (see Appendix A.4).

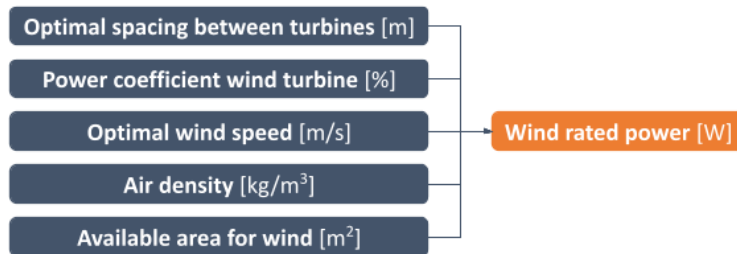
$$C_{wind}(v_r, c, k) = -exp(-\frac{v_f}{c})^k + 3 \cdot c^3 \cdot \frac{\gamma^{(3/k)}}{k(v_r^3 - v_c^3)} \cdot (\Gamma(\frac{3}{k}, (\frac{v_r}{c})^k) - \Gamma(\frac{3}{k}, (\frac{v_c}{c})^k)) \quad (2.5)$$

where:

- v_r is the optimal wind speed (m/s)
- v_f is the cut-out wind speed of wind turbine (m/s)
- v_c is the cut-in wind speed of wind turbine (m/s)

The next step consists of computing the wind rated power. Figure 2.5 contains the data involved in that process.

Figure 2.5: Wind rated power calculation



Parameters involved in the calculation of the wind rated power.

Finally, the formulation of the wind rated power (P_{wind}) is the following:

$$P_{wind} = \frac{1}{2} \cdot c_{p_{max}} \cdot \rho \cdot \frac{\pi}{4n^2} \cdot v_r^3 \cdot A \quad (GW) \quad (2.6)$$

where:

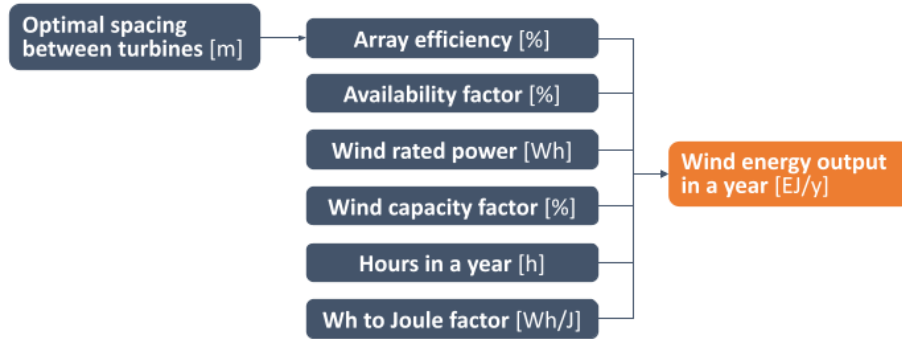
- $c_{p_{max}}$ is maximum wind capacity factor (%)
- n is the optimal spacing between turbines (m)
- A is area considered (m^2)
- ρ is the air density (kg/m^3)

To consider the wind farm array effect, an array efficiency (η) is computed by assuming a 50 x 50 array size, which sets the a and b coefficients:

$$\eta = a \cdot e^{-b \cdot \frac{\pi}{4n^2}} \quad \text{with} \quad a, b = 0.9838, 42.5681 \quad (2.7)$$

Finally, we are able to calculate the energy output for both wind onshore and offshore. Figure 2.6 has all the final components required for the wind energy output calculation.

Figure 2.6: Wind energy output calculation.



Parameters involved in the calculation of wind energy output in a year in EJ. One of the parameters involved, the array efficiency, also depends on the optimal spacing between turbines, set in this study to 50.

The formulation of the wind energy output (E) is, ultimately, the following:

$$E = P_{wind} \cdot C_{wind} \cdot \eta \cdot a_v \cdot h \cdot Wh_to_J / 10^{-9} \quad (EJ) \quad (2.8)$$

where:

- a_v is the area available (%)

- n is the optimal spacing between turbines (m)
- A is area considered (m^2)
- h is hours one year, which is equal to 8760 (h)
- Wh_to_J is the conversion from Wh to Joule (J/Wh)

The significant variation of the wind capacity factor depending on the location results in a notable difference between the rated power (installed capacity) and the effectively energy output available.

2.2.6 Wind uncertainty

For onshore wind, the maximum power coefficient of the wind turbine can vary. Factors like the design and condition of the turbine blades are significant, as well as technological aspects like the precision of the pitch control system. The maximum theoretical value of the performance coefficient is 59.26% according to Betz law. Modern wind turbines achieve peak values for the power coefficient in the range of 45–50%. Therefore, for the base case, it was used in our study the value of 50% for this parameter. The upper bound was the potential with the maximum theoretical power coefficient of 0.59 and the lower bound was the value of 0.41 in order to consider the same percentage variation for both boundaries. In terms of offshore wind, two parameters were considered when calculating the upper and lower bounds: the maximum power coefficient of the wind turbine and the suitability factor depending on the distance to the coast. For the capacity factor, the same values applied onshore were applied for the offshore potential scenarios. For the suitability factor, we employed the NREL constraints for the base case as seen in Table 2.2. The lower bound was defined with more strict constraints defined by the European Union as displayed in Table 2.3 (EEA, 2009). Finally, the upper bound considered a loosening of the NREL constraints by 10%. A compilation of the parameters used for suitability depending on the distance to the coast for each case can be seen in Appendix A.2.

Table 2.3: Local suitability factors based on distance and conditions for the lower bound of offshore wind potential.

Distance/Condition	Local Suitability Factor
0 - 10 km	4%
10km - 50 km	10%
50 km - 160 km	25%
>160 km	0%

2.3 Solar potential

In terms of the solar energy potential, the study by Dupont et al (Dupont et al., 2020) proposes a complete approach. It incorporates multi-criteria constraints, including geographical constraints that differentiate between large-scale power plants and kilowatt-size rooftop solar PV systems based on land use, slope, and suitability factors. The solar resource assessment is central to the methodology, determining the availability and intensity of solar energy in each cell. In our study, we employ a $0.1^\circ \times 0.1^\circ$ as described in the previous section.

2.3.1 Solar technologies

In our study, two solar technologies are considered: photovoltaic panels (PV) and concentrated solar panels (CSP). Concerning PV panels, mono-silicon solar panels are considered, which are made from a single, continuous crystal structure of silicon. These panels typically offer higher efficiency rates due to their uniform crystalline structure, which allows for more effective light absorption.

As to CSP, we are considering solar power towers with salt thermal energy storage (ST-salt-TES). This technology employs a large number of flat mirrors or heliostats to concentrate sunlight onto a central receiver atop a tower. The receiver contains molten salt, which absorbs and stores the heat. This stored thermal energy can be used to produce steam and generate electricity, similarly offering the advantage of energy storage for continuous power supply.

2.3.2 Solar data

The irradiation data is obtained from the Global Solar Atlas (Global Solar Atlas, 2023). The dataset offers a solar resource mapping at 250 m horizontal spacing. Table 2.4 has the main data parameters defined for the computation.

Table 2.4: Main parameters for computation of the solar potential.

Parameter	Value	Unit
PV ground cover ratio	20	%
CSP ground cover ratio	13.33	%
PV performance ratio	50	%
PV degradation ratio	36	%
CSP degradation ratio	20	%
PV design efficiency	24	%
CSP design efficiency	21	%
CSP design irradiance	950	W/m ²
PV lifetime	25	y
CSP lifetime	30	y
Wh to Joule	3600	J/Wh

2.3.3 Area available for solar production

A majority of the land mass is not suitable for solar power deployment, requiring realistic assumptions about the available area. This consideration is important for different solar technology types, including large-scale power plants (several megawatts) and smaller rooftop solar PV panel systems. These two applications have different geographic criteria as they do not compete for the same land area. For large-scale megawatt plants, a suitability factor is associated with each grid cell, defined as the cell's fraction suitable for CSP (Concentrated Solar Power) and PV (Photovoltaic) solar power plant installation. This suitability factor is determined using a three-step process, considering the types of land use suitable for large-scale megawatt plants.

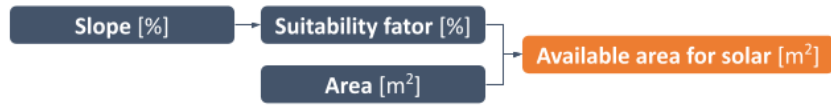
The first step involves selecting types of land use that are suitable for large-scale megawatt solar power plants. This selection is based on assumptions adapted to solar power constraints. The land

cover of each grid cell is determined using the GlobCover 2009 dataset from the European Space Agency (ESA) and the University Catholique de Louvain (UCLouvain) (ESA and UCLouvain, 2019), which classifies global land cover into 22 classes. Certain areas, such as bioreserves and urban areas.

Next, it involves approximating the share of available land suitable for large solar power plants to each grid cell. This share is estimated to be between 5% to 10% of the global area, depending on the land use type and suitability for solar power plants. Finally, an exclusion criterion is applied based on the terrain slope. CSP (Concentrated Solar Power) plants are deemed unsuitable for areas with an average slope greater than 2%, whereas PV (Photovoltaic) plants may be placed in areas with slopes up to 30% (approximately 16.7 degrees). The global terrain slope and aspect database from IIASA (IIASA, 2007), which provides eight classes of terrain slope gradients, is used for this assessment in order to obtain a final suitability factor for each grid cell.

Figure 2.8 contains the parameters involved in the calculation of the available area for solar generation.

Figure 2.7: Available area for solar calculation.



Parameters involved in the calculation of the available area for solar production.

The area of one grid cell is the same as equation 2.1. The formulation of the area available for PV (A_{PV}) and the area available for CSP (A_{CSP}) is then as follows:

$$A_{PV} = a_{cell} \cdot sf_{PV} \quad (m^2)$$

$$A_{CSP} = a_{cell} \cdot sf_{CSP} \quad (m^2)$$

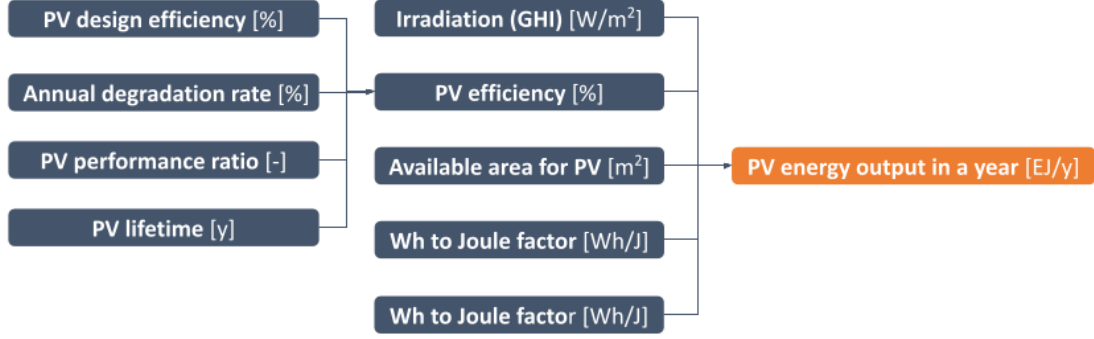
where:

- $sf_{wind}^{onshore}$ is the suitability factor for wind onshore generation in one cell (%)
- $sf_{wind}^{offshore}$ is the suitability factor for wind offshore generation in one cell (%)

2.3.4 Solar potential computation

The parameters involved in the PV energy output can be seen in Figure 2.8.

Figure 2.8: PV solar energy output calculation.



Parameters involved in the calculation of the PV energy output in a year in EJ. One of the parameters involved, the photovoltaic efficiency, also depends on other parameters as indicated in the figure.

The calculation of the solar energy output begins with computing the average solar efficiency (η_{avg}^{PV}) over 25 years, as follows:

$$\eta_{avg}^{PV} = \eta_{PV} \cdot PR \cdot (1 - d_{rate})^{25} \quad (2.9)$$

where:

- η_{PV} is the average efficiency of the PV module (%)
- PR is the performance ratio of the PV module (%)
- d_{rate}^{PV} is the degradation rate of the PV module (%)

Therefore, it is possible to calculate the final PV energy output (E_{PV}):

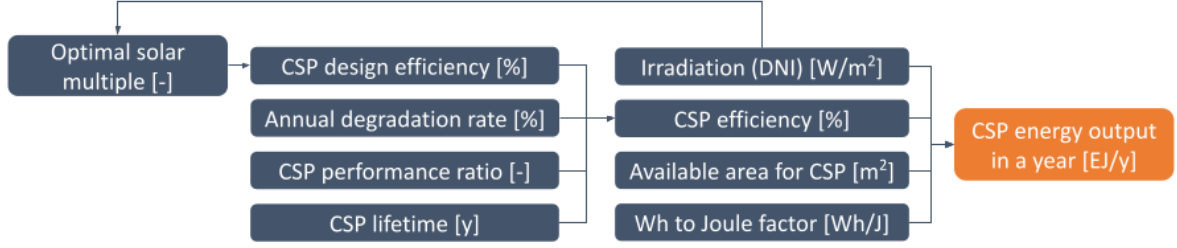
$$E_{PV} = A_{PV} \cdot GHI \cdot GCR_{PV} \cdot Wh_to_J \cdot 10^{-18} \quad (EJ/y) \quad (2.10)$$

where:

- GHI is the Global Horizontal Irradiation (kWh/m^2)
- GCR_{PV} is the ground cover ratio for PV modules (%)

The parameters involved in the computation of the CSP potential are displayed in Figure 2.9.

Figure 2.9: CSP solar energy output calculation.



Parameters involved in the calculation of the CSP energy output in a year in EJ. One of the parameters involved, the CSP efficiency, also depends on other parameters as indicated in the figure. The direct normal irradiation (DNI) is used to compute the optimal solar multiple as well.

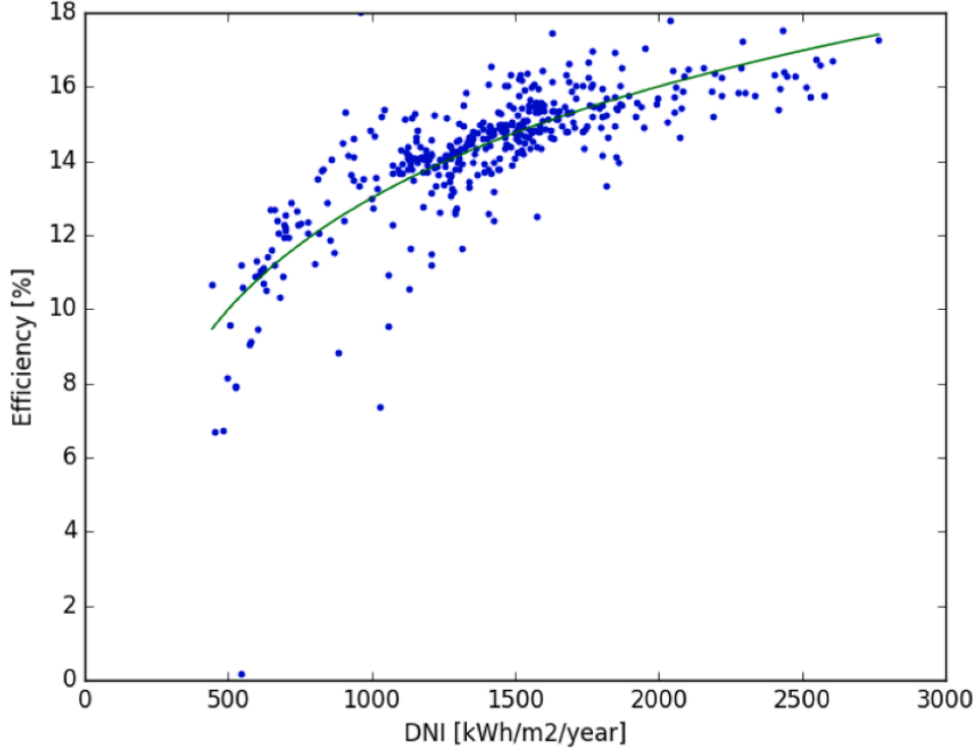
To calculate the CSP solar energy output an extra step has to be taken. To provide for an upper theoretical limit for CSP technologies within constraints, it was necessary to determine the optimal ratio between the size of the solar collector field (measured by aperture area) and the required size of the power block and storage system. We, then, obtain the solar multiple for each cell that provides the optimal conversion from solar energy to electricity.

For this purpose, 400 locations worldwide were chosen using the System Advisor Model (SAM) (Nate et al., 2018). Simulations were run for each location to predict the annual energy production of a power plant across a range of solar multiples. For each simulation, SAM estimates the annual production of the plant based on hourly resolved irradiance data. The solar-to-electric efficiency is calculated afterwards, based on the average DNI of the location and the aperture area (size of the collector field):

$$\eta_{\text{CSP}} = \frac{\text{Annual Production (kWh/y)}}{\text{Aperture Area (m}^2\text{)} \cdot \text{DNI (kWh/m}^2\text{/y)}} \quad (2.11)$$

To find a regression function for the dependence on DNI and the solar multiple, the study analyzed the evolution of efficiency in relation to Direct Normal Irradiance (DNI) for a fixed solar multiple value (SM). The data indicated that efficiency depended on DNI in a logarithmic manner, which can be described by the function type $y = a + b \ln(\text{DNI})$, as seen in Figure 2.10. To determine the parameters a and b , a least squares linear regression was used, resulting in an R-squared value between 0.5 and 0.75, indicating a moderate to strong fit.

Figure 2.10: Evolution of the efficiency with annual solar irradiation of salt thermal energy storage with a solar multiple of 2.7 .



The figure (Dupont et al., 2020) displays the evolution of the efficiency of the solar power towers with salt thermal energy storage with annual DNI, considering a solar multiple of 2.7. The simulation points exhibit a logarithmic dependence

The focus then shifted to how the parameters 'a' and 'b' change with variations in the solar multiple. The solar multiple was simulated within a range of 0.9 to 2 for scenarios without storage, and from 2.5 to 4 for configurations that include 12 hours of storage, with increments of 0.1. These ranges were selected to remain within realistic design configurations according to current standards.

The function for the evolution of the efficiency proposed in the study is therefore of the following form:

$$\eta(DNI, SM) = (a_1 \cdot SM + a_2) \cdot \ln(DNI) + (b_1 \cdot SM + b_2) \quad (2.12)$$

where:

- DNI is the Direct Normal Irradiation (kWh/m^2)

Once the design efficiency of the CSP is obtained, it is possible to calculate the average CSP efficiency (η_{avg}^{CSP}) over its lifetime with the following formulation:

$$\eta_{avg}^{CSP} = \eta_{CSP} \cdot (1 - d_{rate}^{CSP})^{25} \quad (2.13)$$

where:

- η_{CSP} is the average efficiency of the CSP module (%)
- d_{rate}^{CSP} The degradation rate of the CSP module (%)

The final CSP energy output (E_{CSP}) is finally obtained through:

$$E_{CSP} = DNI \cdot 365 \cdot \eta_{avg}^{CSP} \cdot A_{CSP} \cdot GCR_{CSP} \cdot Wh_{to_J} \cdot 1000 \cdot 10^{-18} \quad (2.14)$$

where:

- GCR_{CSP} is the ground cover ratio for CSP modules (%)

2.3.5 Solar uncertainty

In the case of PV potential, three parameters defined the uncertainty: the design efficiency of the panel, the performance ratio, and the degradation ratio. All these parameters influence directly the overall PV efficiency (see Figure 2.8) and, therefore, impact the energy output of this technology. In the case of the mean value, the cell efficiency was determined by taking into account upcoming cell technology with improved efficiency, including passivated emitter and rear cell (PERC) designs and heterojunction cells (Yu et al., 2018). Therefore, industry expectations are of an average cell efficiency of 25%, for heterojunction cells (with a market share of 15%) and of 24% for PERC cells (with a market share of 70%). Based on these evaluations an efficiency of 24% was utilized as a reasonable estimate for conversion efficiencies that will be reached around 2030. For the lower bound, we considered a scenario where the efficiency is not improved. The average efficiency of mono-silicon cells sold in 2018 was estimated at 21.5% based on industry surveys (Trube, 2016), so this value was applied for the lowest case. Finally, for the upper bound, the same percentage variation was applied, with an efficiency of 26.5%.

The average value for Performance Ratio (PR) has been established in the global methodology guidelines on life cycle assessment of photovoltaic electricity published by the IEA. Based on a literature review a default PR value of 80% can be used (Fthenakis et al., 2011), which was then used for our base case. The recommendations were endorsed based on an evaluation of 300 solar-PV systems data from 2006 and 2014 located in France, UK, Belgium and Spain (Jonathan et al., 2015). The analysis applied a Weibull distribution with individual systems ranging from 60% to 90% at extremes when looking at data from a large sample of solar-PV plants, with a mean and median around 80%. The PR of large megawatt-scale solar power plants in Thailand was evaluated obtaining PR's between 75% and 80% when regularly cleaned (Nattakarn Sakarapunthip, 2017). The PR for a 300 kW-PV system of Biola University in Norwalk, China was evaluated at 75% to 85% for mono-Si PV (Li., 2018). Based on the evaluation of the studies mentioned, we were able to define an upper limit of 85% and lower bound of 75% as it encompasses the different realities of the world.

Finally, the degradation rate takes into account the performance decline over time caused by smaller or larger failures of technology components (Halwachs et al., 2019). An extensive literature review of 2000 studies with published degradation rates since the 1960s (D. C. Jordan, 2013). Their median degradation rate for mono-Si modules was established at 0.36% for installations after 2000. Based

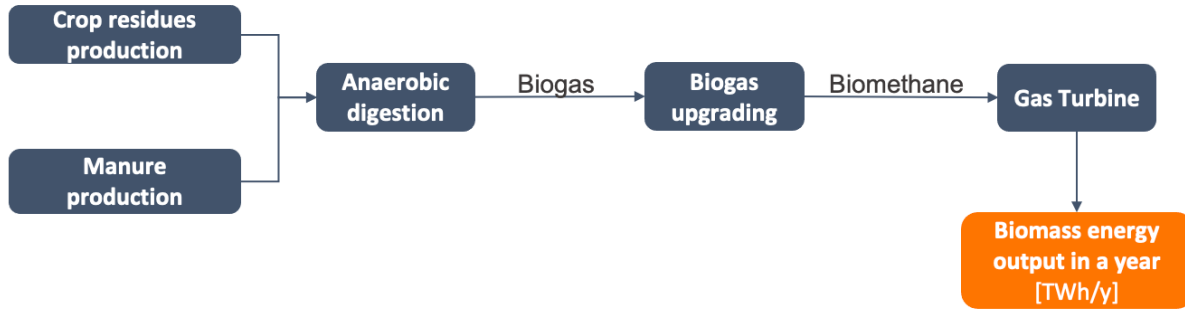
on this evaluation a value of 0.5% per year was used for the base case and a variation of 2.5% was considered for upper and lower boundaries.

2.4 Biomass potential

Regarding the assessment of biomass potential, our analysis focuses on the conversion of feedstocks into biomethane through the process of anaerobic digestion.

Anaerobic digestion is a technology designed to break down wet biomass feedstocks, such as crop residues and livestock manure, yielding biogas and digestate as outputs. The composition of biogas typically consists of around 60% methane and 40% carbon dioxide, presenting versatile applications such as local heating or combined heat and power production. Alternatively, energy producers have the option to upgrade biogas to biomethane, a fuel possessing akin properties to conventional fossil natural gas. The conversion of biogas into biomethane holds the potential to foster the development of a circular economy. This transformative process entails the purification of biogas by eliminating impurities such as CO_2 and H_2S . The resulting biomethane can then be seamlessly integrated into the natural gas grid, serving dual purposes in heating applications and as a sustainable transportation fuel (Marconi and Rosa, 2023). Figure 2.11 displays this methodology graphically.

Figure 2.11: Biomass energy output methodology.



Methodology used to compute the the electricity production potential from biomass.

2.4.1 Biomethane yields from biomass

For the purpose of estimating the availability of waste biomass, this study incorporates two primary biomass feedstocks, namely crop residues and livestock manure. The analysis relies on spatially explicit biomass availability data, obtained at a resolution of 10 km worldwide, sourced from a comprehensive database (Feng and Rosa, 2023). Results are depicted in Table 2.5.

Table 2.5: Country biomass availability.

Country	Crop residues (Mt/y)	Manure (Mt/y)
Belgium	4.38	30.91
Japan	11.29	53.85
South Korea	6.96	46.32
Trinidad and Tobago	0.08	0.91

The coefficients employed for estimating the potential production of biomethane from biomass represent experimental biomethane yields acquired following a 30-day digestion period (Li et al., 2013). Owing to the limited data available regarding the distribution of these samples across the majority of the examined countries, we opted for using mean values with a biomethane density of 0.671 kg/m^3 . The estimated biomethane yields for crop residues are 0.17 kg methane per kg of volatile solid (kg_{VS}), while for livestock manure, the biomethane yields are estimated at 0.1494 kg of methane per kg_{VS} . Detailed figures can be found in Table 2.6. As mentioned above, the coefficients utilized are mean values that do not consider the weight of each sample in each country. However, we were able to calculate a weighted coefficient for manure in Belgium (Scarlat et al., 2018), and the resultant coefficient is not significantly different from the average (0.21 and 0.15 kg of methane per kg_{VS} respectively). Details of the calculation can be found in Appendix A.5.

Table 2.6: Biomethane yields from crop residues and livestock manure.

Biomass type	Samples	Biomethane potential (ml/g_{VS})	Biomethane potential (kg/kg_{VS})	Average biomethane potential (kg/kg_{VS})
Crop residues	Corn	241	0.1617	0.1729
	Rice	287	0.1926	
	Wheat	245	0.1644	
Manure	chicken manure	295	0.1979	0.1494
	Dairy manure	51	0.0342	
	Swine manure	322	0.2161	

An average concentration of volatile solids has also been employed for each biomass type. This results in concentrations of 78.8% and 23.43% for crop residues and livestock manure, respectively (Li et al., 2013).

Table 2.7: Biomethane Production by Country.

Country	Biomethane production from crop residues (Mt/y)	Biomethane production from manure (Mt/y)	Total biomethane production (Mt/y)
Belgium	0.5973	1.0822	1.6796
Japan	1.5388	1.8855	3.4243
South Korea	0.9486	1.6218	2.5704
Trinidad and Tobago	0.0103	0.0318	0.0422

2.4.2 Biomass potential calculation

We assume the final energy is generated through a 40% efficiency open-cycle gas turbine (OCGT). Utilizing a Lower Heating Value (LHV) of 36 MJ/m³ (IEA, 2020), we ultimately calculate the estimated power production from biomass for each country, and these results are summarized in Table 2.8.

Table 2.8: Power generation from biomass.

Country	Power generation from crop residues (TWh/y)	Power generation from manure (TWh/y)	Total power generation (TWh/y)
Belgium	3.56	6.45	10.01
Japan	9.17	11.24	20.41
South Korea	5.65	9.67	15.32
Trinidad and Tobago	0.06	0.19	0.25

2.4.3 Biomass uncertainty

To incorporate an uncertainty factor regarding biomass potential, we opted to vary two coefficients: biomethane yields from biomass and OCGT (Open Cycle Gas Turbine) efficiency. Instead of using a mean coefficient for the biomethane potential of each type of biomass, we employed the minimum and maximum values for the lower and upper bounds, respectively. Each of these values ultimately contributes to a final lower or upper bound value by incorporating an uncertainty coefficient of 10% on the efficiency of the OCGT (varying from 30% to 50%).

2.5 Hydropower potential

Hydropower is a time-tested form of renewable energy that explores the kinetic and potential energy of water to generate electricity. Historically, this form of energy has been utilized for centuries and today is a critical component of the global energy mix. The scale of the plants can vary widely, from massive dams and reservoirs that power entire regions to small-scale and even micro-scale systems that provide localized power with minimal environmental impact. The adaptability of hydropower is one of its greatest strengths, allowing it to be tailored to the specific needs and topographies of different locales.

Environmental considerations are integral to the development of hydropower projects. While hydropower is lauded for producing clean energy with a significantly lower carbon footprint than fossil fuels, it is also scrutinized for potential impacts on local ecosystems and communities. Modern engineering and ecological science have thus focused on developing sustainable hydropower practices that mitigate environmental disruption and foster a harmonious balance between energy production and natural preservation.

In our study, following the global tendencies, we do not consider an expansion of the hydro power systems of the studied countries. The hydropower potential is then derived from the existing plants in the respective countries. For this investigation, we rely on the estimated electricity genera-

tion from hydropower plants for the year 2017. (Global Energy Observatory, Google, KTH Royal Institute of Technology in Stockholm, Enipedia, World Resources Institute, 2018).

2.6 Hydrogen potential

Hydrogen is widely acknowledged as a versatile and clean energy carrier with the potential to play a significant role in a sustainable energy future. It has a high energy content per unit of weight (Edwards P.P and W.I.F, 2007), making it particularly useful in weight-sensitive applications such as transportation or aerospace. When hydrogen is used in a fuel cell to produce electricity, it combines with oxygen from the air to produce water, emitting no carbon dioxide or pollutants. This makes it an attractive option for reducing greenhouse gas emissions, especially in sectors that are difficult to decarbonize with direct electrification, unlike fossil fuels. However, the energy efficiency of the entire hydrogen cycle, from production to utilization, and the infrastructure required for its widespread adoption, remain ongoing challenges.

There are three main production routes of hydrogen: electrolytic (from water and electricity), biogenic (from woody biomass and biogenic waste) and fossil (from coal and natural gas). In this study, it is only considered the electrolytic production of hydrogen through electrolysis (Yue et al., 2021), which involves splitting water (H_2O) into its basic components, hydrogen (H_2) and oxygen (O_2), using electricity. For the hydrogen to be considered renewable, the electricity must come from renewable sources such as wind, solar, or hydroelectric power, which is the case of our study.

Electrolysis involves the use of an electrolyzer, a device that contains an anode and a cathode submerged in a water-based electrolyte. Passing electricity through the electrolyzer causes the water molecules to split at the electrodes, producing hydrogen gas at the cathode and oxygen gas at the anode. The efficiency of this process has been a significant focus of research, as it impacts the viability and cost-effectiveness of producing renewable hydrogen. The efficiency can vary depending on the type of electrolyzer used. There are three main types of electrolyzers: alkaline electrolyzers, proton exchange membrane (PEM) electrolyzers, and solid oxide electrolyzers. Alkaline electrolyzers, which are the most traditional, typically have energy efficiencies in the range of 62-82% (Yue et al., 2021). The advantages of this technology is its good durability and maturity, as well as its lower costs compared to the others. In our study, for the base case, we will consider the use of AEL with an efficiency of 62% so we can have a more challenging scenario. To account for the variations this process can have, an uncertainty of 10% is added to the potential, ranging the efficiency from 50% to 70%.

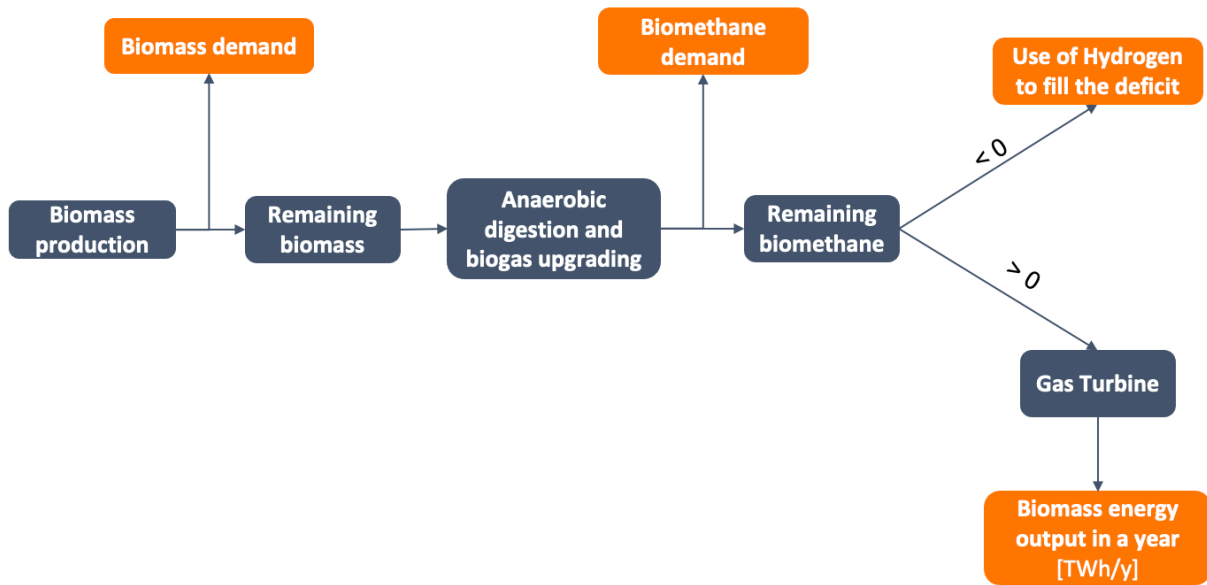
2.7 Aggregation in total demand and total production potential

The demand that we aim to address only constitutes a portion of the 2050 projected demand. Specifically, the renewable potential of each country will predominantly contribute to the production of electricity and hydrogen through electrolysis. Consequently, for the purpose of assessing only electricity and hydrogen demand, only selected sources will be considered for the comparison between demand and production. These sources are electricity, hydrogen, biomethane, biomass, industrial heat, and ammonia, collectively representing 65% of the total final consumption for each

country (the other 35% cannot be replaced either by electricity or hydrogen as discussed in Section 1.1). The demand for biomass and biomethane will be directly met with available biomass. Ammonia and industrial heat demands will be added to hydrogen demand (after transformation in the case of ammonia, as explained below). Consequently, we are left with two distinct demands: electricity and hydrogen.

Taking into account the projected demand for biomass and biomethane, there is a need to consider how much of the biomass potential will be used to fulfill this direct demand in order to arrive at a biomass potential that can effectively be used to produce electricity. We first subtract the biomass demand from the available biomass quantity. To achieve this, the biomass demand must be converted into tons of crop residues or tons of manure, considering their respective LHV. Average LHV have been calculated based on (Singh et al., 2008) and (Sahu et al., 2016). After analysis, it turned out that the scenario resulting in the highest electricity generation is the one where the biomass demand is fulfilled using available livestock manure. The remaining quantity of biomass is then converted into biomethane (refer to Section 2.4) and finally, we subtract the biomethane demand from the resulting quantity of biomethane. In some countries, the produced biomethane is insufficient to meet the demand, necessitating the use of hydrogen to fill the deficit (see Figure 2.12). Clearly, these countries will consequently be unable to generate electricity from biomass and their hydrogen demand will be increased.

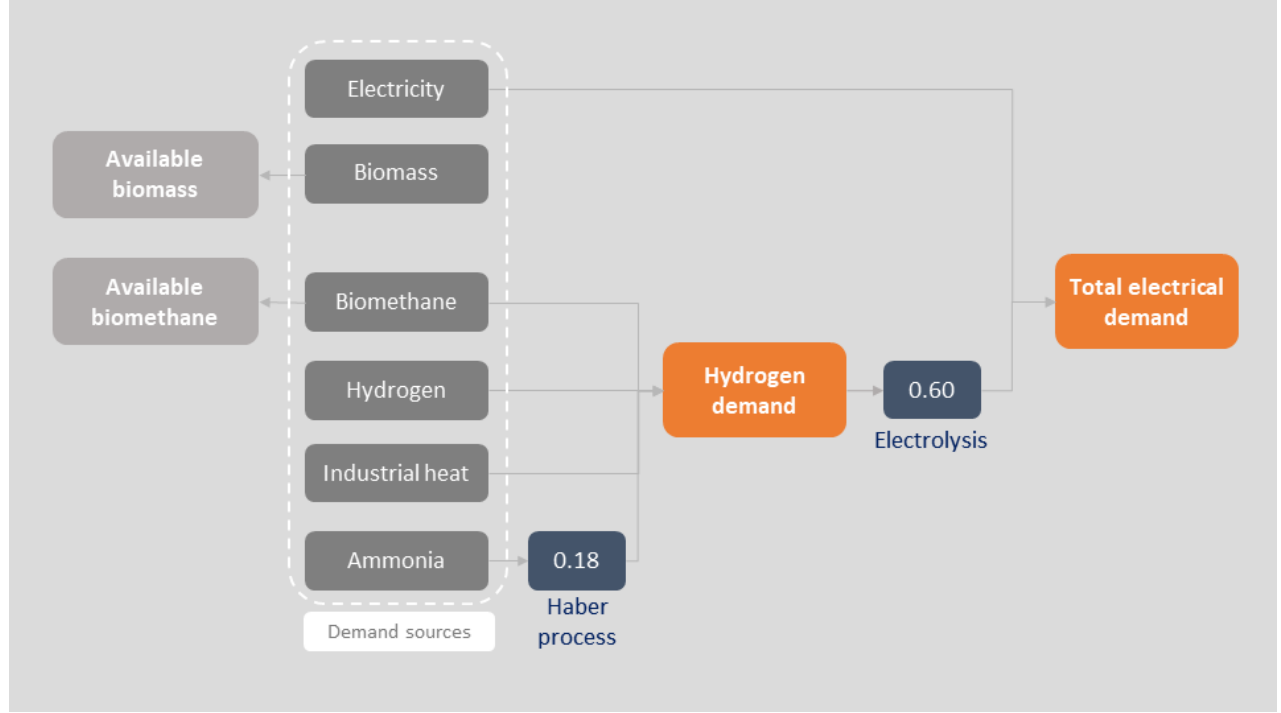
Figure 2.12: Scenarios of biomass potential with biomass and biomethane demand accounted.



Once this process is done, a new final biomass potential is obtained, allowing us to have a usable

technical potential to meet the demand. Moreover, an important step should be taken to compare the demand with the electricity production, which is the conversion of each demand to electricity units (TWh_{elec}/y). As the renewable potential provides only electricity in this study, non-electric sources must be transformed into their electrical equivalent. This allows for a meaningful comparison between the total renewable potential production and the demand. Figure 2.13 displays the relation between different sources and their electrical equivalent.

Figure 2.13: Relation between accounted demand sources and their electrical equivalent.



The light grey boxes display the available biomass and the available biomethane which are used to meet the direct biomass and biomethane demand. The grey boxes represent the different demand sources of 2050 that we try to meet with renewable potential. They are connected to blue boxes that contain the conversion factor leading to a final electrical demand (TWh_{elec}/y). Finally, the orange boxes represent the hydrogen demand and the total electrical demand.

As explained before, the biomass demand is met by the available biomass, and the biomethane demand is partially met by the biomethane produced (refer to Figure 2.12). In case the biomethane demand cannot be met directly by biomethane, the remaining demand is added to the hydrogen demand. We also sum the projected hydrogen demand and the industrial heat demand into the hydrogen demand. Finally, in the case of ammonia, there is a step of conversion that accounts for the stoichiometry of the process. The Haber process, also known as the Haber-Bosch process, is a method for synthesizing ammonia from nitrogen and hydrogen gas under high pressure and temperature. According to Equation 2.15, 177 kg of H_2 and 823 kg of N_2 are theoretically necessary to produce 1 ton of ammonia.



Consequently, a factor of 0.18g of hydrogen per g of ammonia has to be included when converting ammonia to hydrogen. Next, we want the hydrogen demand to be expressed in terms of electricity, so the electrolysis efficiency of 60% has to be applied to the total hydrogen demand. The final total electrical demand is a result of the sum of the electricity demand and the hydrogen demand after accounting for the electrolysis,

We also ought to account for the uncertainty of the demand in electricity and hydrogen. An uncertainty of 10% is applied to the electricity demand to take into consideration the projection unpredictability. The same factor of 10% is applied to the hydrogen demand uncertainty. On top of that, the uncertainty of the electrolysis process is added as described in Section 2.6.

Chapter 3

Results and discussion

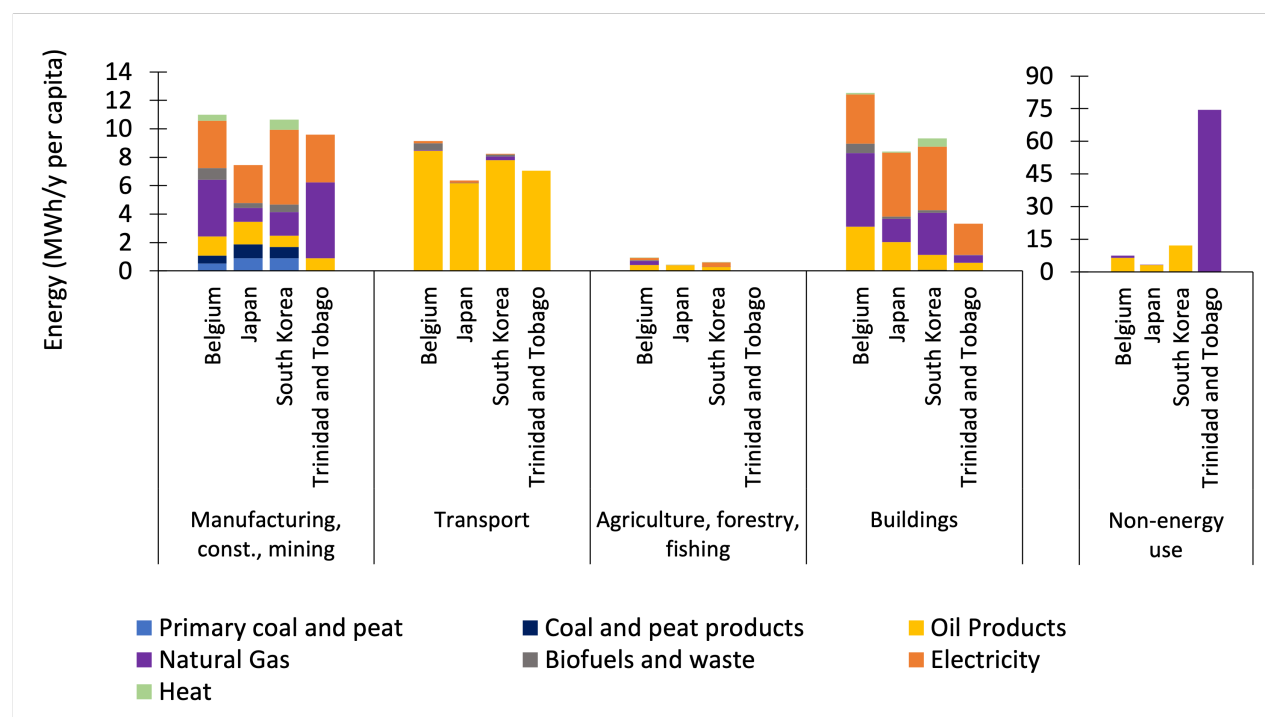
3.1 Energy demand analysis

In this section, we analyse country’s specific energy demand and compare it with the current energy supply. First, we provide a country specific breakdown of the total final consumption per demand sector. Then, we describe the sources of supply based on internal production, import or export.

3.1.1 Country-specific final energy consumption

In this section, we analyze the energy consumption by sector in Belgium, South Korea, Japan, and Trinidad and Tobago. The data are derived from the United Nations Statistics Division (United Nations, 2022) and refer to the year 2019. Figure 3.1 presents how the demand is distributed among different categories and which energy sources are employed. The term “non-energy use” in the figure refers to the utilization of energy sources and their derivatives as raw materials for the manufacture of products outside the scope of the Standard International Energy Product Classification (SIEC), which is delimited by fuels used as sources of energy and electricity that are produced by an economic unit (including households). Hence, non-energy use refers to direct uses that do not involve using the products as a source of energy. Examples of processes from oil products are lubrication, sealing, preservation, road surfacing, and use as a solvent. From natural gas, the main non-energy uses are dedicated to the production of fertilizers, methanol, and other chemicals. Non-fuel uses of coal include chemical products such as refined coal tar which is used in the manufacture of chemicals, for example, creosote oil, naphthalene, phenol, and benzene.

Figure 3.1: Country energy demand per capita in 2019.



Comparison of demand for energy per capita in selected countries in 2019. The figure indicates each country's energy demand per capita in 2019 (MWh/y per capita) (United Nations, 2022). The graph is divided into different sectors and its colors indicate the primary source of that demand. The most significant energy demand is the non-energy category, which is depicted in a different scale.

In the first category, which includes manufacturing, construction, and mining, the countries exhibit similar behavior. For these sectors, electricity and natural gas serve as the primary sources of energy. In terms of transport, countries rely heavily on oil-based products, with minimal electrification of the sector. Notably, road transport is the primary mode (see Appendix B.1) and Belgium presents biowaste as its second main source of transportation fuel. Furthermore, there is a greater demand for aviation in the peninsula and island nations in comparison to Belgium (see Appendix B.1).

Trinidad and Tobago does not present an energy demand for agriculture and forestry. The other nations exhibit a small energy requirement for that sector, which is supplied mainly by oil products and electricity. Trinidad and Tobago distinguishes itself in terms of commerce and public services, owing to its lower consumption. Given the country's smaller population, the count of services to be provided is reduced.

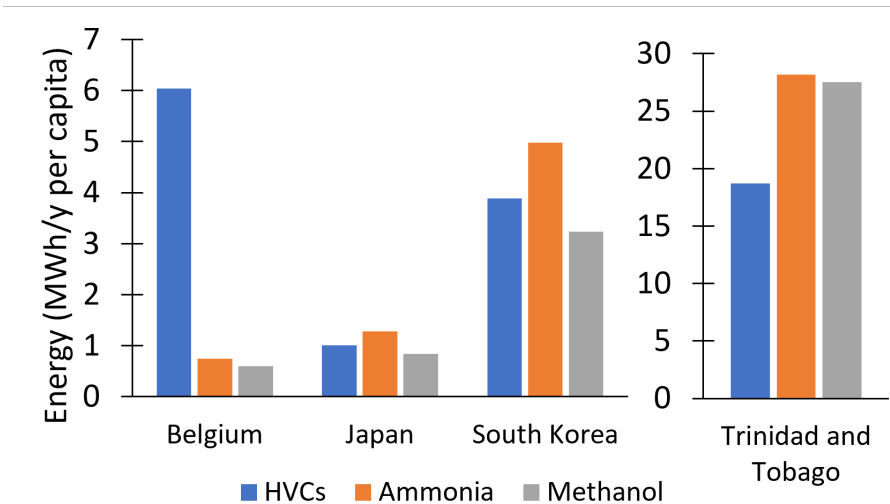
As for households, Belgium displays a considerably higher consumption rate. This could be related to the lower average temperature compared to the other countries with an annual mean temperature of around 10°C. The four countries are mainly dependent on natural gas and electricity to supply this demand.

Belgium, Japan, and South Korea predominantly depend on oil products. In contrast, Trinidad

and Tobago not only has a significantly higher consumption per capita but also depends exclusively on natural gas, owing to its abundant natural reserves. Natural gas is an abundant source of hydrocarbons, primarily composed of methane (CH_4), which can be effectively used in many chemical manufacturing processes. The country’s primary exports (see Appendix B.3) consist of ammonia, acyclic alcohols, petroleum oils, ferrous products and mineral or chemical nitrogenous fertilizers (Gaulier and Zignago, 2010).

Figure 3.2 illustrates the non-energy end products of each country per capita in 2019. Figure 3.3 depicts the absolute non-energy end products of each country in 2019.

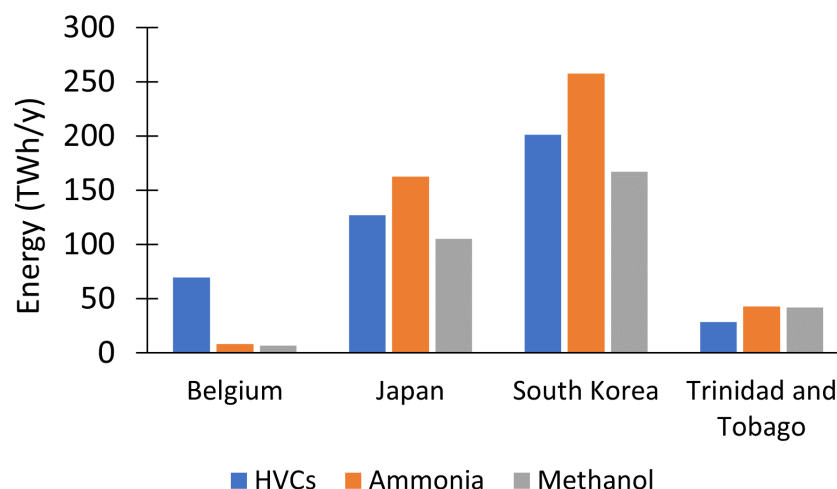
Figure 3.2: Country non-energy end products per capita in 2019.



Analysis of non-energy end product production per capita in selected countries, 2019. The figure presents the per capita production of ammonia, High-value chemicals (HVCs), and methanol from non-energy inputs. The results are derived from a calculation based on chemical production shares by region worldwide (IEA, 2018a). The production of Trinidad and Tobago is depicted in a different scale.

Belgium has notably a higher production of HVCs compared to its ammonia and methanol production. Japan and South Korea, on the other hand, show a balanced distribution of these products. Finally, Trinidad and Tobago, as a notable exporter, has significantly higher values. It is also interesting to notice that the country is mostly focused in ammonia and methanol since these products can be produced with natural gas. Additionally, it is crucial to assess the environmental impact of energy sources in each country. Upon analysis of the proportion of energy derived from renewable sources, it is found that the percentage of energy derived from renewables accounts for only 1% to 2.4% of the total per capita energy consumption (see Appendix B.2).

Figure 3.3: Country non-energy end products in 2019.



Analysis of non-energy end product production in selected countries, 2019. The figure presents the per capita production of ammonia, High-value chemicals (HVCs), and methanol from non-energy inputs. The results are derived from a calculation based on chemical production shares by region worldwide (IEA, 2018a).

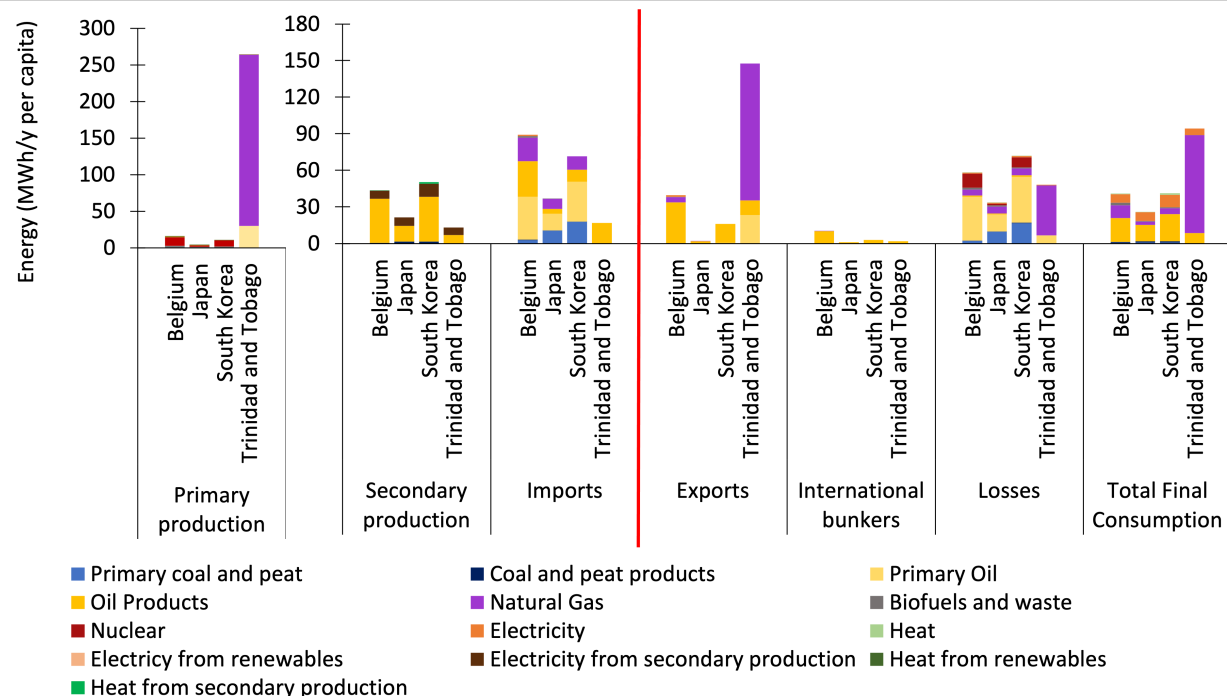
The country with the highest production is South Korea, followed by Japan. Subsequently, we find Trinidad and Tobago, and finally Belgium, both with significantly lower production.

3.1.2 Country-specific energy balance

In this section, we discuss the energy balance by sector in Belgium, South Korea, Japan, and Trinidad and Tobago. The data comes from the United Nations Statistics Division (United Nations, 2022) and refers to the year 2019.

Figure 3.4 presents information on the energy supply and demand for each country in 2019.

Figure 3.4: Country energy balance per capita in 2019.



Comparison of energy balance per capita in selected countries in 2019. The figure displays the per capita energy balance of each country (MWh/y per capita) (United Nations, 2022). On the left side of the red bar are the per capita energy production and imports of the countries, and on the right side are their per capita energy exports, associated with losses or consumption.

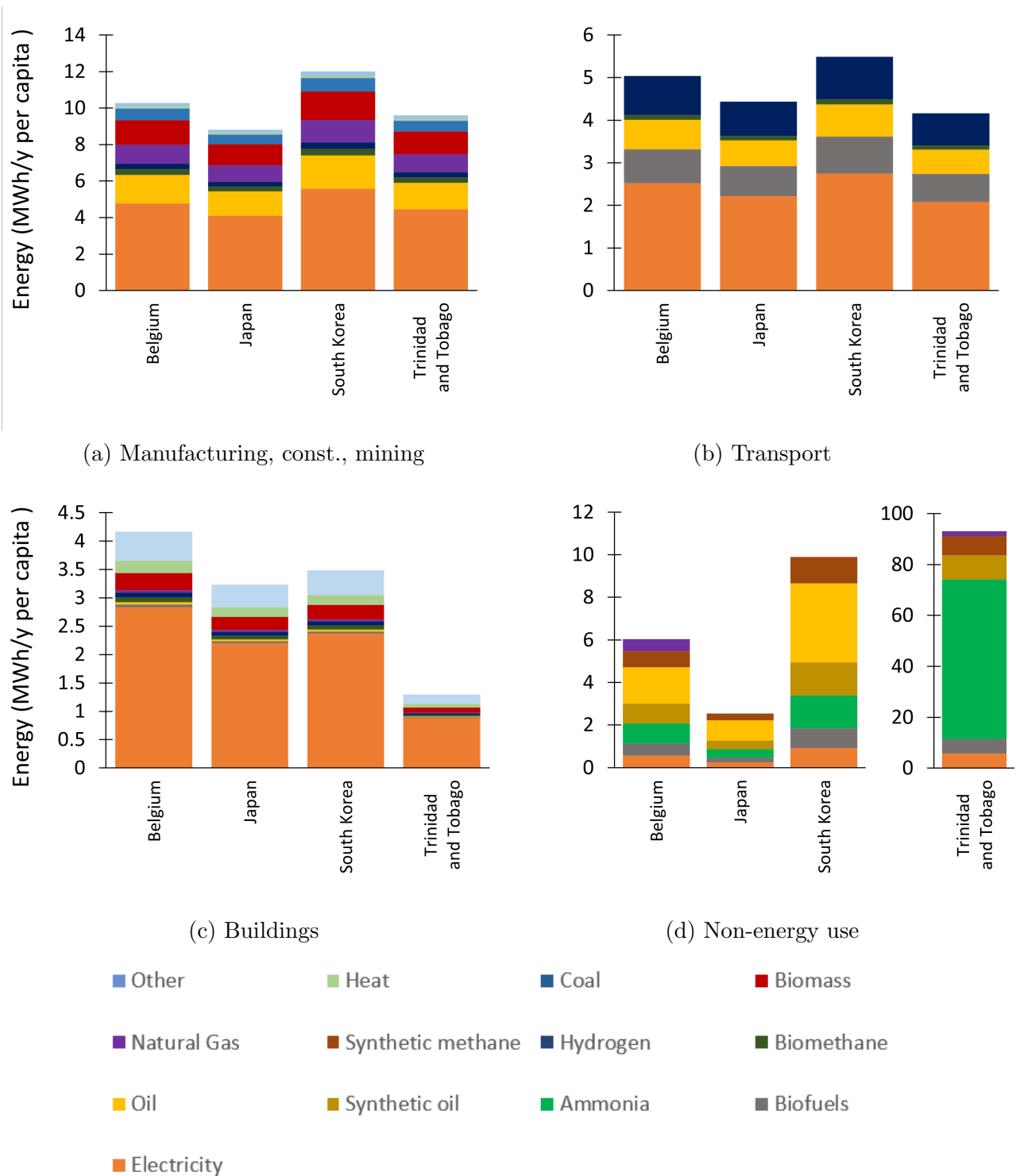
Understanding the energy supply of the countries studied is crucial in revealing their current energy mix and future options for achieving net zero emissions. From Figure 3.4, Belgium, Japan, and South Korea depend on nuclear facilities for their primary energy production. Current global policies, including Belgium’s 2003 law of nuclear power phase-out, suggest that moving away from this source is imminent. Conversely, Trinidad and Tobago contribute significantly to natural gas production, as previously explained. In all countries, the majority of secondary production is linked to oil products. In terms of energy exchange, Belgium is the largest importer, particularly of primary oil and its derivatives. In contrast, Trinidad and Tobago can be identified as the largest exporter, with significant exports of natural gas and oil.

3.1.3 Net-zero emissions scenario

In this section, we evaluate a possible 2050 net-zero emissions scenario for each country. As mentioned in section 2.1, the forecast presented is based on the global projection made by the International Energy Agency (IEA, 2021). This report represents an extensive evaluation of the steps necessary to achieve a net-zero emissions system by 2050. This involves ensuring reliable and economical energy supply, promoting universal energy access, and supporting economic growth.

Figure 3.5 displays the 2050 energy demand for each sector, separately obtained from the methodology explained in Section 2.1.

Figure 3.5: Country energy demand per capita projected to 2050.



Comparison of the projected demand for energy per capita in selected countries in 2050. The figure indicates each country's energy demand per capita in 2050 (MWh/y per capita) (IEA, 2021). Coal, Oil, and Natural Gas refer to the use of these products with CCUS or unabated (fossil fuels produced and used without interventions that substantially reduce the amount of greenhouse gas emitted).

The most significant shift that can be seen in Figure 3.5 is the electrification of the system, with most of the demand being supplied by renewable energy. Electrification plays a vital role in reducing emissions. Electric vehicles (EVs), electric heating systems, and industrial processes powered by electricity can significantly reduce the dependence on fossil fuels. The shift to EVs can substantially decrease emissions from one of the largest emitting sectors. The IEA notes that the transportation sector accounts for a significant portion of global CO₂ emissions. In the industry, electrification of processes, such as electric arc furnaces in steel production, can significantly reduce emissions. Transitioning from fossil fuel-based heating systems to electric alternatives like heat pumps can decrease residential and commercial building emissions. Nevertheless, the shift to electricity demands a robust and reliable energy grid, capable of handling increased loads and the intermittent nature of renewable energy sources. Certain industrial processes and heavy transportation modes, like aviation and shipping, present significant challenges for electrification due to current technological constraints and are expected to still depend on fossil fuels. Moreover, the initial cost of transitioning to electric technologies can be high. Evidently, there are social challenges, such as ensuring equitable access to these technologies and managing the workforce transition in industries affected by electrification.

As mentioned in Section 1.1, it is projected the continued dependency of some sectors on fossil fuels. The graphs show the use of coal, oil, and natural gas, whose values refer to both their use with CCUS or unabated. In 2050, the global NZE scenario by IEA witnesses a total consumption of about 120 EJ of fossil fuels compared to 460 EJ in 2020. This persisting use of fossil fuels in 2050 can be attributed to three primary factors, despite the energy sector emitting no net CO₂. First, the utilization for non-energy purposes, as it can be seen in Figure 3.5. More than 30% of the total fossil fuel consumption in 2050 within the net-zero emissions scenario, including 70% of oil usage, occurs in applications where the fuels are not burned, thereby resulting in no direct CO₂ emissions. Examples of such applications include their use as chemical feedstocks, lubricants, paraffin waxes, and asphalt (IEA, 2018a). Although efforts are being made to curtail fossil fuel usage in these applications, such as a global increase in plastic recycling rates from 15% in 2020 to 55% in 2050, fossil fuel consumption in non-energy applications continues to rise slightly by 2050. Secondly, the use with CCUS where approximately half of the fossil fuel consumption in 2050 takes place in facilities equipped with CCUS technology. Furthermore, a lot of natural gas can be converted to hydrogen using CCUS. Finally, the use in sectors with limited technological alternatives. The remaining 20% of fossil fuel consumption in 2050 within the net-zero emissions scenario occurs in sectors where completely eliminating emissions is particularly challenging. Primarily, this pertains to oil, as it continues to be the primary fuel source for aviation. A small quantity of unabated coal and natural gas is used in industry and energy production. This unabated fossil fuel consumption is fully compensated for by Bioenergy with Carbon Capture and Storage (BECCS) and Direct Air Carbon Capture and Storage (DACCS) technologies, enabling the reaching of a net-zero emissions scenario.

For manufacturing, construction, and mining, the use of biomass is notable as one of the main new sources for these sectors. Hydrogen also appears as a complementary source. These fields are projected to still depend on coal, oil, and natural gas, which require the procedures mentioned above.

The transport sector sees a significant participation of hydrogen as fuel, which is the largest share of hydrogen between all different categories. Hydrogen is especially promising for heavy-duty and long-

haul transport, such as trucks, buses, ships, and potentially airplanes, where high energy-density fuel is required. The development of hydrogen refueling infrastructure is critical, with a need for strategic deployment of refueling stations, particularly along heavy freight corridors. High costs and technological challenges are significant barriers to the widespread adoption of hydrogen, with a significant need in advances in technology to make the technology competitive. The IEA underlines the importance of policy support, including funding for research and development, incentives for vehicle purchase and infrastructure development, and international collaboration to harmonize standards and regulations. Moreover, the use of biofuels should also increase in the sector. The IEA sees significant potential in the development of advanced biofuels that do not compete with food production. These include biofuels produced from non-food biomass like agricultural residues, waste, and dedicated energy crops grown on non-arable land. As for hydrogen, the development of the biofuel industry is dependent closely on government policies.

For the buildings' use, which includes households, commerce, and public services, not only the electrification of these sectors is noticeable, but also the increase in the use of biomass. The modernization and sustainable management of biomass use in households is vital for achieving global energy, environmental, and health goals.

3.2 Technical potential

In this section, we will discuss the results obtained from the different methodologies used for the country's renewable potential. We are going to assess an optimal energy mix and whether this technical potential could meet the demand of each country. In case a country can not be self-sufficient in the 2050 net-zero emissions scenario, we will also suggest an importation scenario to fulfill the needed electricity.

Figures 3.6 to 3.12 illustrate the spatial distribution of studied renewable potentials in each national zone (and Exclusive Economic Zone (EEZ) for offshore wind potential). Figure 3.13 displays an overview of the country's renewable resources and their 2050 demand projection. Finally, Table 1.1 presents the annual renewable potential per technology for each country.

Figure 3.6: Spatial distribution of onshore wind potential by country.

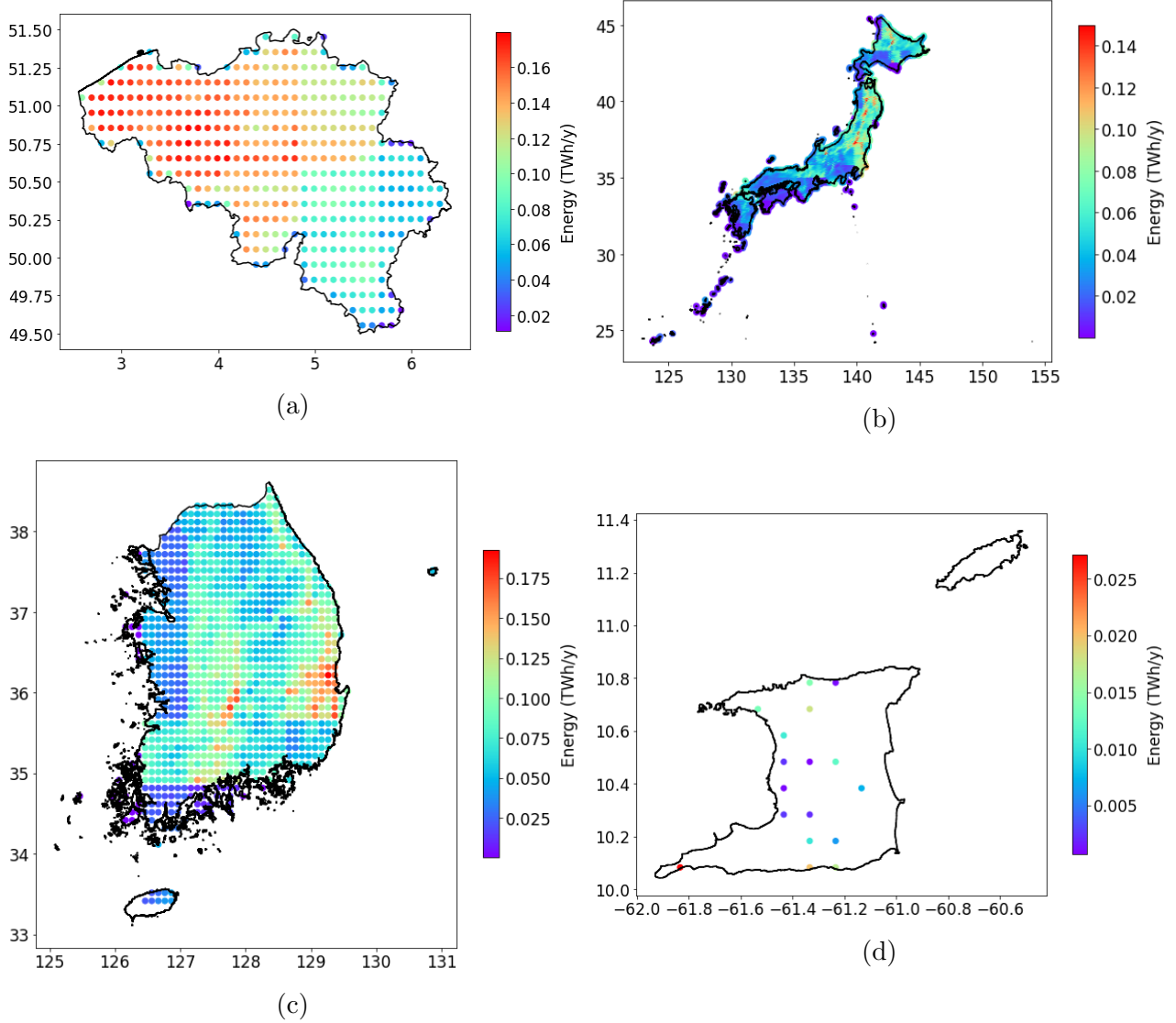


Figure 3.6 displays the wind onshore potential of the BEKOJAT countries. Belgium (Figure 3.6(a)) shows a higher offshore wind potential in its northwest and coastal regions, which aligns with its flat terrain and coastal geography that favor wind energy capture. The southwest region of Belgium is generally less favorable for wind energy production, especially due to the topography. This part of the country features hilly terrain, abundant with forests, especially in the Ardennes region. These geographical features can disrupt the smooth flow of wind, causing turbulence and reducing wind speeds at ground level. Therefore, the region experiences lower average wind speeds compared to coastal and elevated regions in Belgium. Additionally, the regions have a higher concentration of protected areas, which impacts significantly the suitability factor of these cells.

Over 70% of Japan's land area is mountainous, with the Japanese Alps running through the central part of Honshu, the largest island (Huddle et al., 2010). As mentioned above, this topography can

be challenging to capture. However, the northeast region of Japan (Figure 3.6(b)) displays a higher onshore wind potential, particularly the Tohoku area, due to several interrelated geographical and meteorological factors. The topography of the northeast region plays a crucial role since it features a mix of mountainous landscapes and coastal plains. This diverse topography affects wind patterns significantly; as winds travel over the region, they are funneled through valleys and accelerated over ridges, often leading to increased wind speeds, particularly in mountain gaps which act as natural wind channels. We also find fewer metropolitan areas in the region, which increases its suitability factor. The country also counts 29.75% of its land occupied by protected areas, which limits its onshore wind potential.

South Korea (Figure 3.6(c)) demonstrates a dense concentration of wind potential in its eastern region, which is due to its higher wind speeds. The western part of the country, where the capital Seoul is located, presents a lower potential, precisely due to the greater urban areas.

Finally, Trinidad and Tobago (Figure 3.6(d)) presents an overall small onshore wind potential. The country does not experience the high wind speeds typically found in higher latitude regions. The equatorial location means that the islands are subject to relatively stable, but generally low-speed, trade winds. Furthermore, in an island nation with rich biodiversity and ecosystems, we find larger nature-protected areas covering 30% of the country's land.

Figure 3.7: Spatial distribution of offshore wind potential by country.

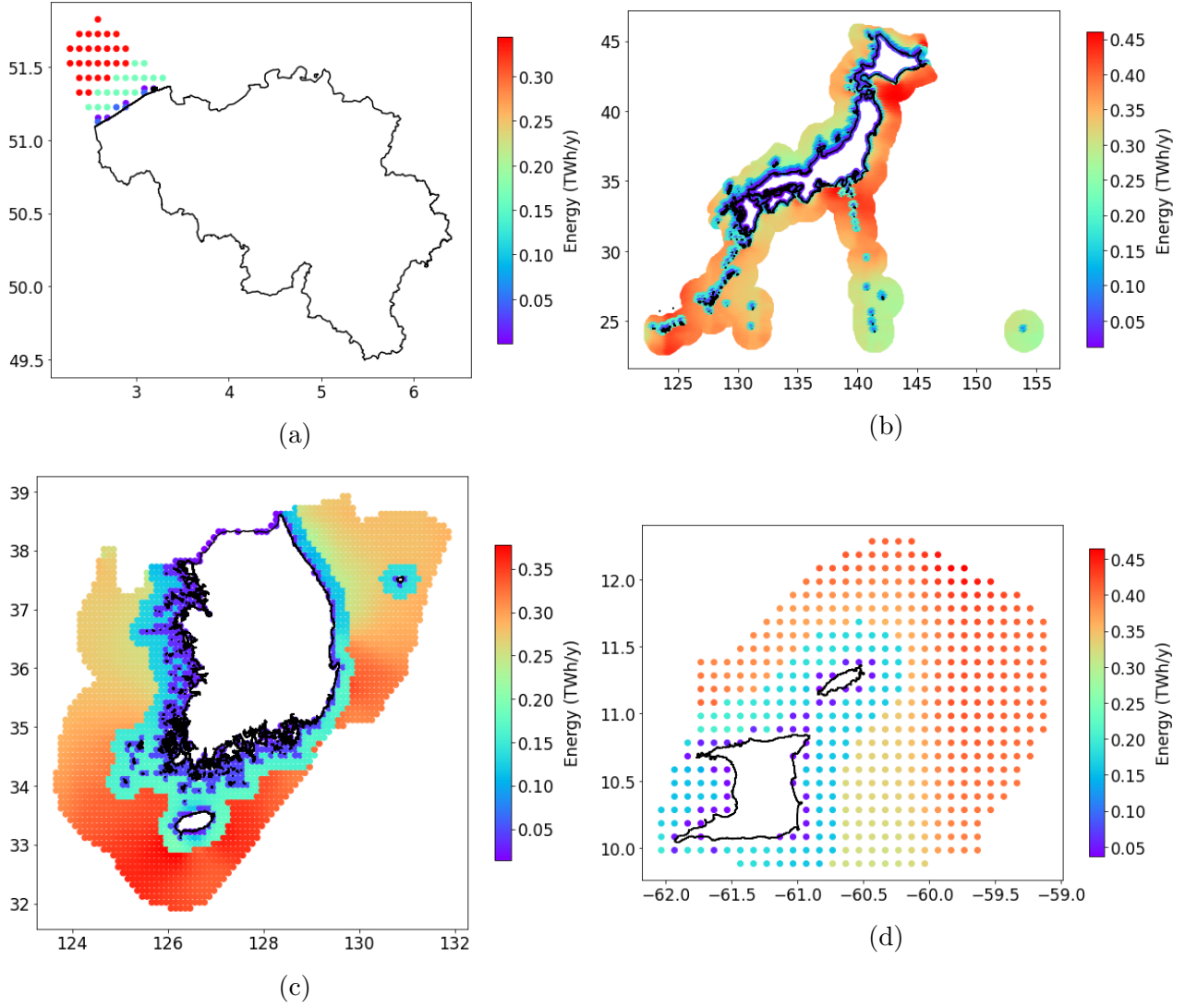


Figure 3.7 displays the wind offshore potential of the BEKOJAT countries. Among all the countries, analyzed in this study, Belgium (Figure 3.7(a)) has the smallest Exclusive economic zone (EEZ). Despite its relatively small coastline along the North Sea, Belgium has positioned itself as a leader in offshore wind power. The combination of shallow waters and strong, consistent winds makes it an ideal location for harnessing wind energy.

Japan (Figure 3.7(b)), on the other hand, has the biggest EEZ in the world, with 4.47 million km² of extension. With a coastline stretching almost 30000 kilometers, Japan has a significant potential for offshore wind. Addressing Japan's weather conditions is a primary focus. The country's deep coastal waters and susceptibility to earthquakes and typhoon winds require expert local knowledge to optimize wind energy resources (Heger, 2016). Researchers are working on developing typhoon-resistant, offshore wind turbines and floating offshore wind turbine demonstration projects.

South Korea's (Figure 3.7(c)) offshore wind energy sector presents a significant opportunity for the country's renewable energy progress, especially on the Yellow Sea, on its western coastline, as can be seen in the figure. Moreover, one of the regions with the highest potential is located south, near South Jeolla Province, which has got the attention of the country's government and regional leaders. These areas are favorable for their strong wind resources and suitable maritime and industrial infrastructure.

Trinidad and Tobago (Figure 3.7(d)) has a significant potential for wind resources in its offshore regions, with an EEZ of approximately 74199 km². A high potential can be seen in the northern part of the zone, in the Atlantic Ocean.

As explained in Chapter 2, the energy output obtained represents the practical available energy and cannot be converted to an installed capacity with one constant factor since the wind capacity factor significantly shifts depending on the location analyzed. The obtained installed capacities for wind and solar generation (see Equations 2.6 for wind) can be seen in Appendix B.4.

Figure 3.8: Spatial distribution of PV potential by country.

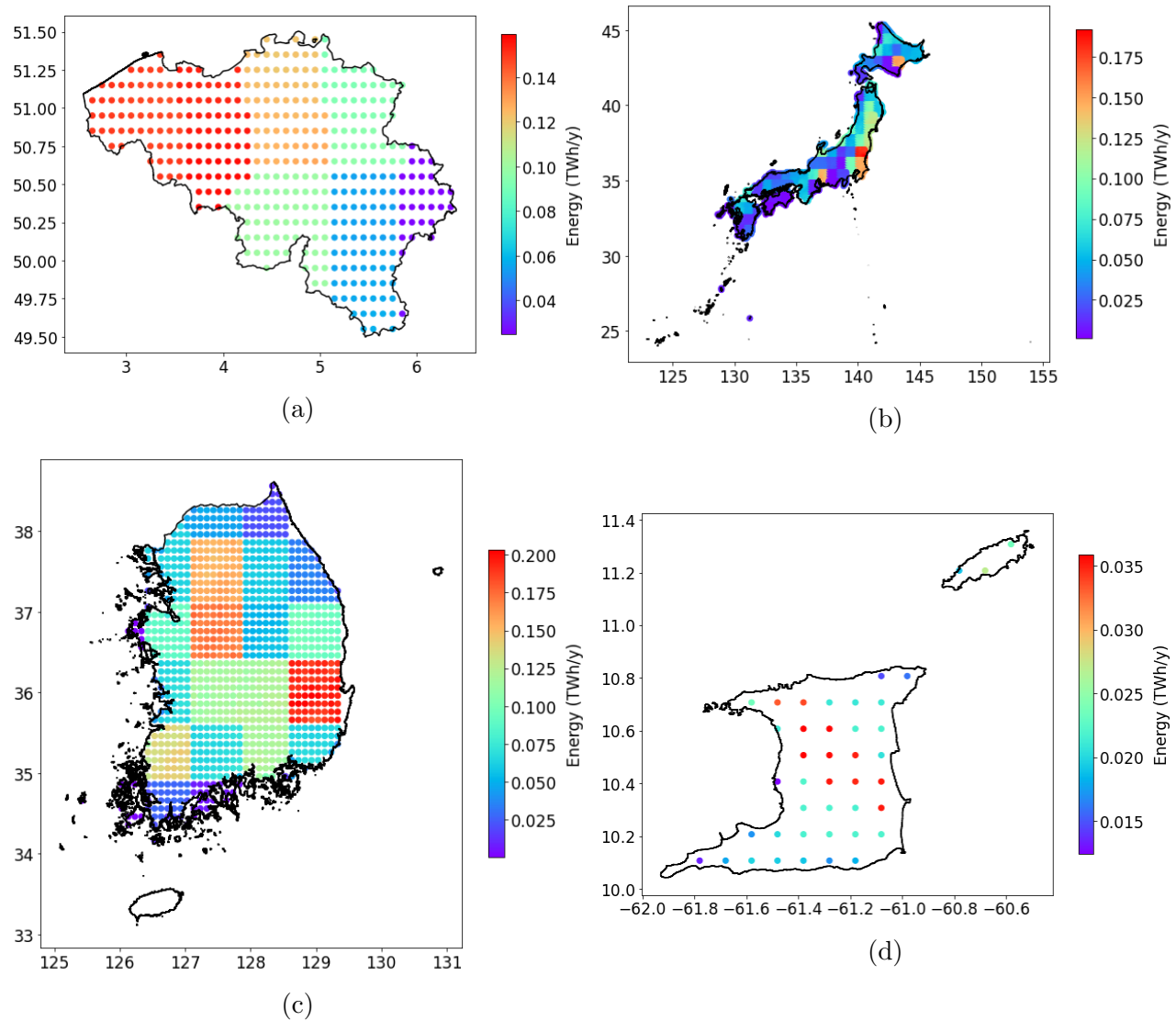


Figure 3.8 displays the spatial distribution of PV potential in the countries analyzed. Belgium (Figure 3.8(a)) shows a higher potential in the northern part of the country, where more suitable regions are found, as well as better irradiation values. Japan (Figure 3.8(b)) has a quite uniform PV distribution. South Korea (Figure 3.8(c)) presents a better PV potential on the western part of the country, similarly to Trinidad and Tobago (Figure 3.8(d)).

Figure 3.9: Spatial distribution of CSP potential by country.

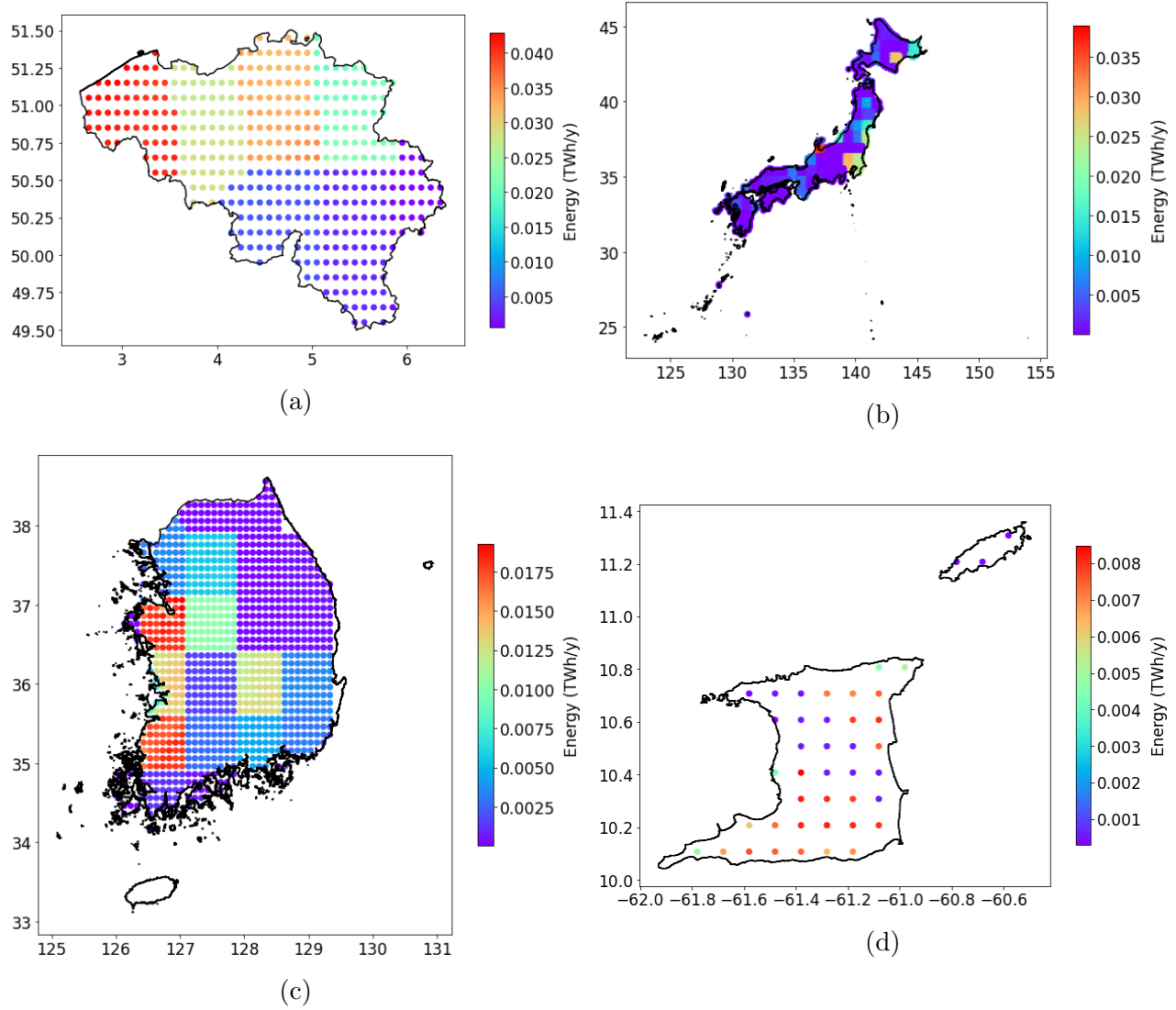


Figure 3.10: Spatial distribution of crop residues potential by country.

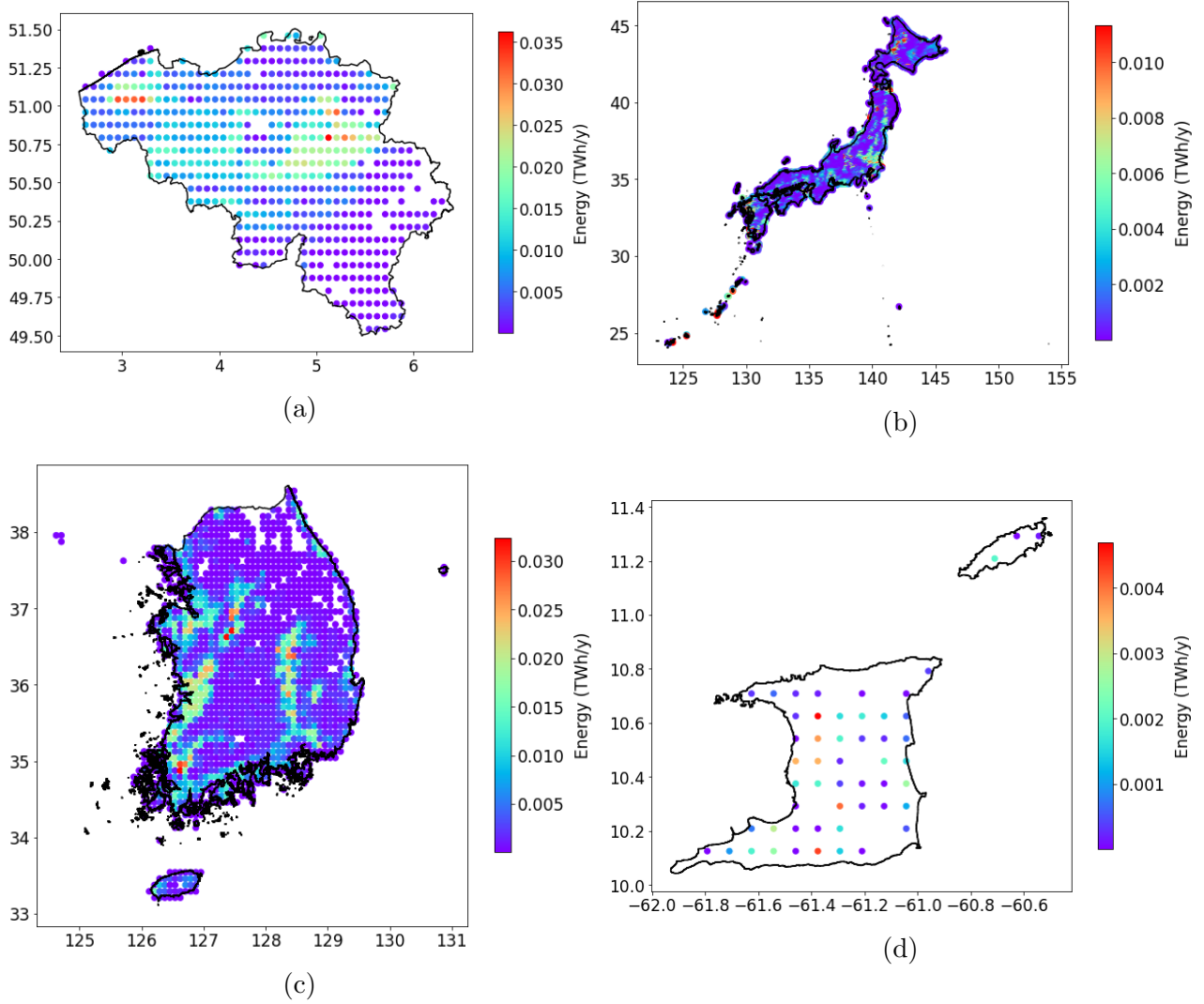


Figure 3.10 shows the crop residues potential of the countries. Crop residues are usually left in the agricultural fields after the crop has been harvested. They include stalks, leaves, husks, and pods. Common examples are straw from wheat or rice, corn stover (leaves, stalks, and cobs left after corn is harvested), and sugarcane bagasse. Therefore, we usually see higher biomass potential from this source close to agricultural regions. The map of Belgium (Figure 3.10(a)) has a higher biomass availability in the eastern region. The map of Japan (Figure 3.10(b)) shows that in the south we can see higher crop residues potential, especially on the southern island of Kyushu. The northern island of Hokkaido is also known for its agricultural profile, so it can also be an interesting source of residue. South Korea (Figure 3.10(c)) has the highest potential appearing to be concentrated in the western part of the country. This could correlate with South Korea's topography and land use where the western regions are more conducive to agriculture, while the eastern part is more mountainous and less suited for large-scale farming. Finally, Trinidad and Tobago (Figure 3.10(d)) has higher crop residue potential on the western part of the island, but, in general, the country does

not present high biomass availability.

Figure 3.11: Spatial distribution of livestock manure potential by country.

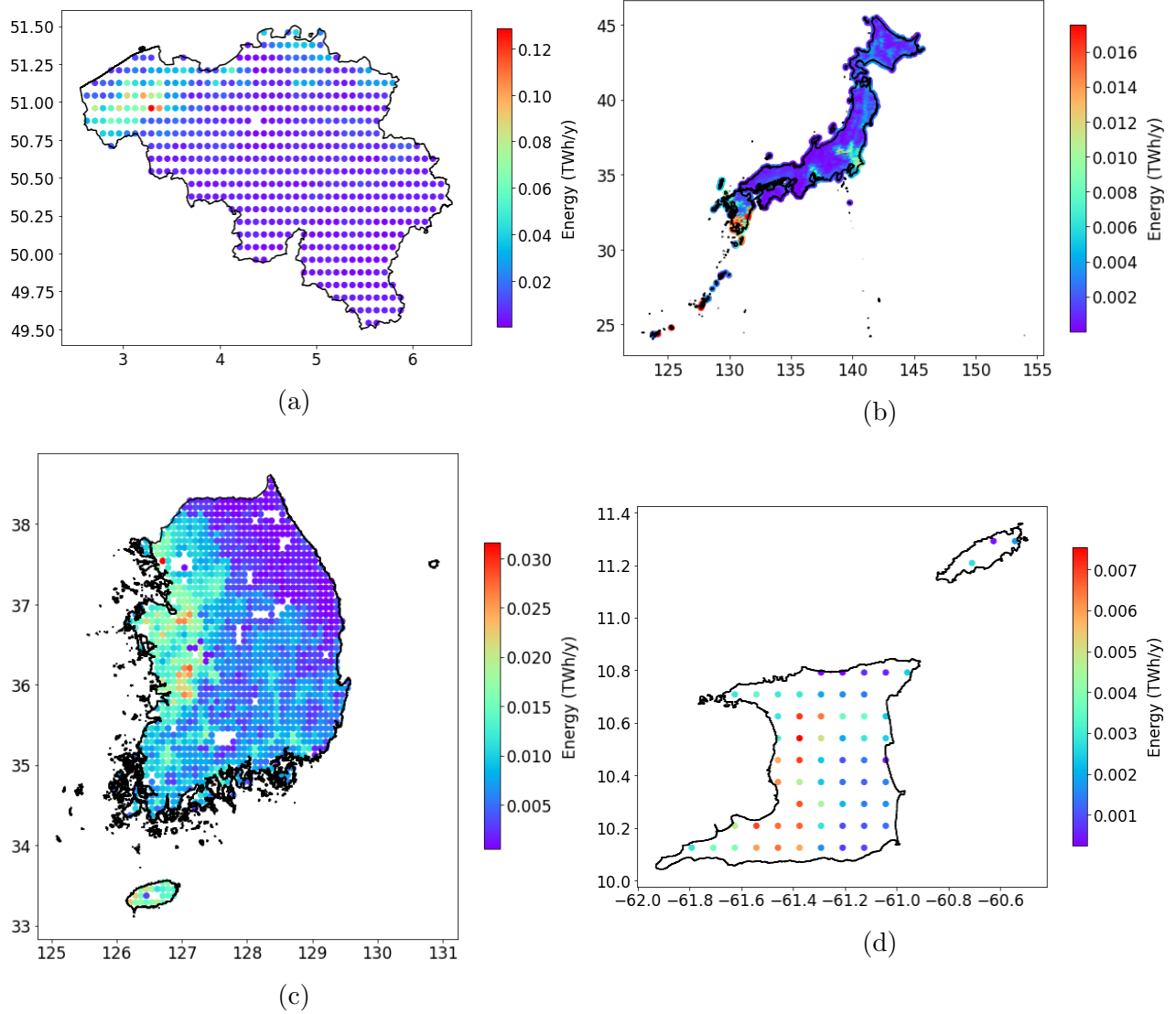


Figure 3.11 shows the manure potential of the countries. Biomass from manure primarily comes from livestock and poultry farming. It is a by-product of animal husbandry and includes a variety of waste materials. Hence, we expect to see higher potential in areas with pecural activities. In Belgium (Figure 3.11(a)), the map shows a concentration of manure potential in the north of the country, close to the coast, which is indeed the region with intensive livestock farming. South Korea (Figure 3.11(c)) shows a dense cluster of high-potential manure along the western coast, particularly in the northwest region near the Seoul metropolitan area, which is corroborated by very high livestock in these regions. Trinidad and Tobago (Figure 3.11(d)) presents a higher manure potential compared to its crop residues potential.

Figure 3.12: Spatial distribution of hydro potential by country.

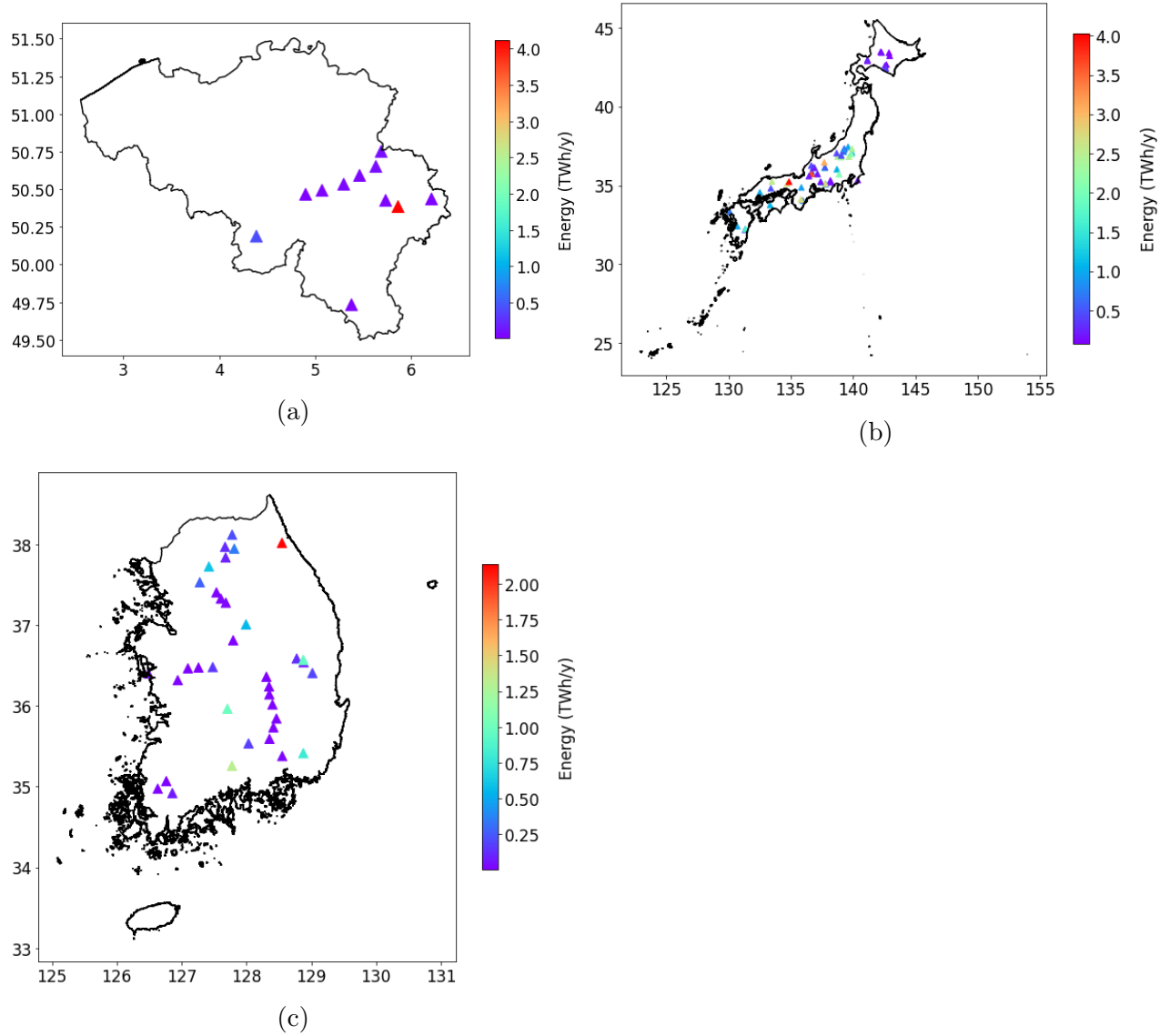


Figure 3.12 presents the hydro potential already installed in the countries. Each triangle refers to an installed hydropower plant since we are not projecting an expansion of hydro production in the future. It can be seen that Japan has the most plants compared to the others, while Trinidad and Tobago does not have this technology employed in the country. Table 1.1 exhibits the technical potential computed per technology for each country, as well as its uncertainties.

Table 3.1: Annual renewable potential per technology for each country.

Technology and scenario for renewable potential (TWh/y)		Belgium	Japan	South Korea	Trinidad and Tobago
Wind onshore	Lower	13.61	136.41	56.59	0.14
	Reference	44.54	166.35	69.01	0.17
	Upper	52.55	196.30	81.43	0.20
Wind offshore	Lower	3.17	1276.85	158.97	43.09
	Mean	11.94	4552.31	570.13	155.63
	Upper	17.07	6322.25	803.06	216.99
PV	Lower	33.97	137.44	72.43	0.82
	Reference	41.33	167.21	88.11	1.01
	Upper	49.51	200.33	105.57	1.19
CSP	Lower	7.59	15.82	4.55	0.18
	Mean	7.76	13.33	4.70	0.19
	Upper	11.77	16.89	4.87	0.19
Biomass (crop residues)	Lower	2.50	6.44	3.97	0.04
	Reference	3.56	9.17	5.65	0.06
	Upper	4.96	12.77	7.87	0.09
Biomass (manure)	Lower	1.11	1.93	1.66	0.03
	Reference	6.45	11.24	9.67	0.19
	Upper	11.66	20.32	17.48	0.34
Hydropower	-	4.88	58.85	9.32	0.00

3.3 Potential vs. demand

After calculating the technical renewable potential, a comparative analysis between the potential and the demand can be conducted. Table 1.1 indicates that PV technology exhibits higher potential than CSP technology, leading to the selection of PV technology for solar potential. Using the projected demand for 2050 (refer to Section 3.1.3), it is feasible to compute both electricity and hydrogen demand.

As explained in Section 2.7, since biomass and biomethane are components of the demand we aim to address, the available potential of these sources will be diminished, potentially leading to an increase in hydrogen demand in the event of a deficit. After accounting for this biomass and biomethane use of the potential, we obtain the usable renewable potential. Table 3.2 provides an overview of this usable potential for each country. Japan and Trinidad and Tobago will consistently rely on hydrogen to address the deficit in biomethane. Belgium, on the other hand, can meet the demand in all scenarios, while South Korea falls short in the worst-case scenario. Subsequently, the hydrogen demand for each country is adjusted accordingly for each scenario.

After accounting for this biomass and biomethane use of the potential, we obtain the following usable renewable potential in Table 3.2.

Table 3.2: Annual usable renewable potential per technology for each country.

Technology and scenario for renewable potential (TWh/y)		Belgium	Japan	South Korea	Trinidad and Tobago
Wind onshore	Lower	13.61	136.41	56.59	0.14
	Mean	44.54	166.35	69.01	0.17
	Upper	52.55	196.30	81.43	0.20
Wind offshore	Lower	3.17	1276.85	158.97	43.09
	Mean	11.94	4552.31	570.13	155.63
	Upper	17.07	6322.25	803.06	216.99
PV	Lower	33.97	137.44	72.43	0.82
	Mean	41.33	167.21	88.11	1.01
	Upper	49.51	200.33	105.57	1.19
Biomass	Lower	1.58	0.00	0.00	0.00
	Mean	6.51	0.00	0.85	0.00
	Upper	11.66	0.00	4.80	0.00
Hydropower	-	4.88	58.85	9.32	0.00
Total electricity production	Lower	57.21	1609.55	297.30	44.05
	Mean	109.19	4944.71	737.42	156.80
	Upper	135.68	6777.73	1004.17	218.38

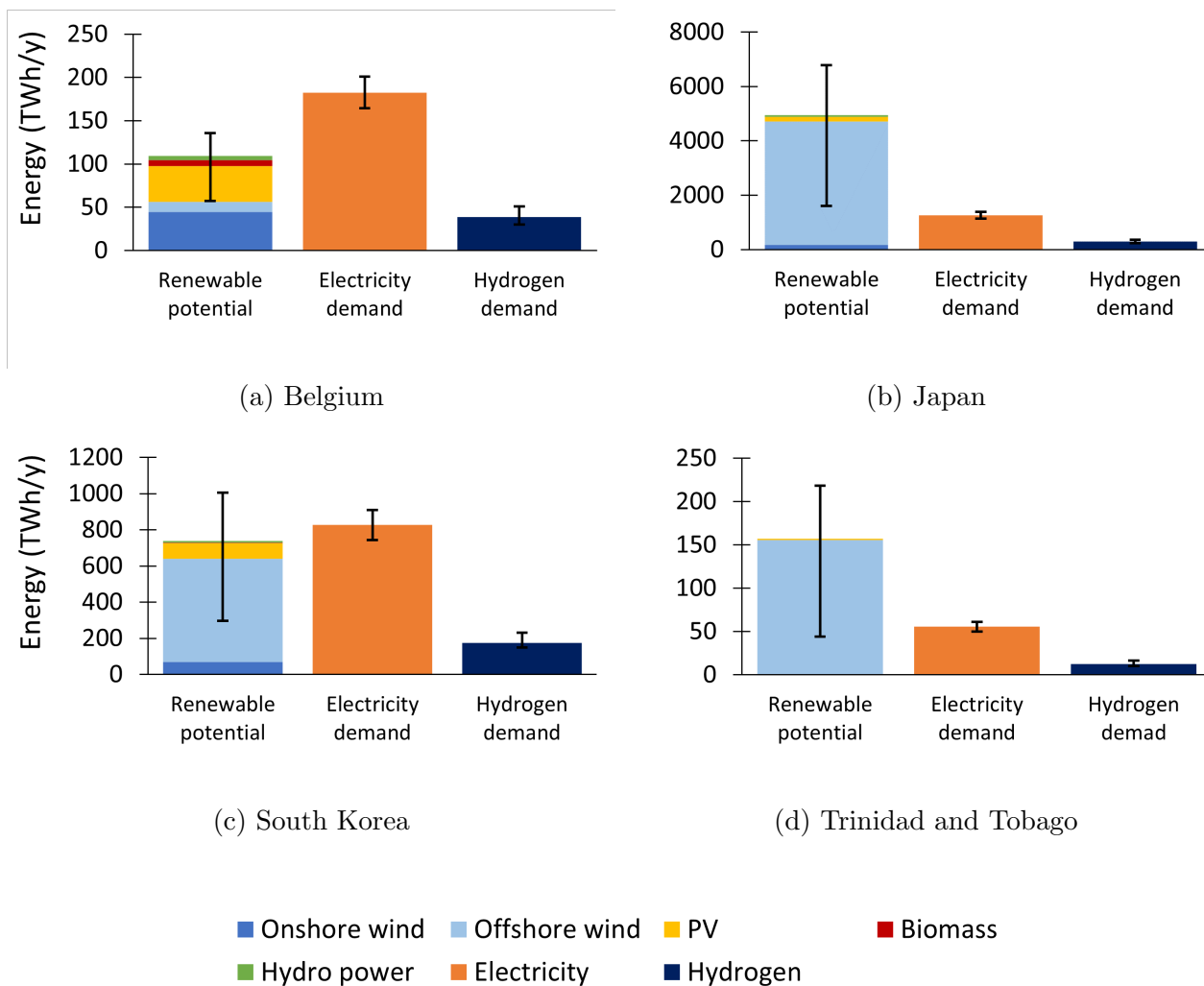
In accordance with the methodology outlined in Section 2.7, the computation of electricity demand and total hydrogen demand is possible. To derive a comprehensive total electrical demand, the hydrogen demand is converted into an electricity equivalent demand for hydrogen production. Following these steps, we arrive at the final total electrical demand. Table 3.3 shows the obtained hydrogen and electricity demand.

Table 3.3: Projected hydrogen and electricity demand.

	Scenario	Belgium	Japan	South Korea	Trinidad and Tobago
Electricity demand (TWh _{elec} /y)	Lower	164.20	1139.35	743.79	50.02
	Reference	182.45	1265.95	826.44	55.58
	Upper	200.69	1392.54	909.08	61.14
Electricity demand for hydrogen production (TWh _{elec} /y)	Lower	29.78	238.17	147.64	10.00
	Reference	38.60	291.19	174.84	12.60
	Upper	50.95	368.72	230.79	16.37
Total electrical demand (TWh _{elec} /y)	Lower	193.98	1377.52	891.43	60.02
	Reference	221.05	1557.14	1001.28	68.19
	Upper	251.64	1761.26	1139.87	77.51

After the computation, Figure 3.13 and Table 3.4 display the final comparison.

Figure 3.13: Country's Renewable Resources and 2050 Demand Projections.



Comparative analysis of the renewable potential and projected electricity and hydrogen demands (TWh/y) for selected countries in 2050. Hydrogen demand is an electricity demand for producing the required hydrogen. An uncertainty of 10% was applied to the electricity demand, while the hydrogen demand uncertainty is described in Section 2.7. The different renewable sources uncertainties are thoroughly described in Chapter 2.

Table 3.4: Total annual usable renewable potential and electrical demand.

Scenario	Total electricity production (TWh _{elec} /y)			Total electrical demand (TWh _{elec} /y)		
	Lower	Mean	Upper	Lower	Mean	Upper
Belgium	57.21	109.19	135.68	193.98	221.05	251.64
Japan	1609.55	4944.71	6777.73	1377.52	1557.14	1761.26
South Korea	297.30	737.42	1004.17	891.43	1001.28	1139.87
Trinidad and Tobago	44.05	156.80	218.38	60.02	68.19	77.51

Based on Table 3.4, we obtain the matrices in Figure 3.14 that enable the visualization of the different scenarios for each country. In each scenario, the deficit or surplus is indicated based on the demand case.

Figure 3.14: Demand-Production Matrix comparison.

Demand scenario \ Production scenario	Lower	Reference	Upper
Lower	-71%	-74%	-77%
Reference	-44%	-51%	-57%
Upper	-30%	-39%	-46%

(a) Belgium

Demand scenario \ Production scenario	Lower	Reference	Upper
Lower	+17%	+3%	-9%
Reference	+259%	+218%	+181%
Upper	+392%	+335%	+285%

(b) Japan

Demand scenario \ Production scenario	Lower	Reference	Upper
Lower	-67%	-70%	-74%
Reference	-17%	-26%	-35%
Upper	+13%	+0%	-12%

(c) South Korea

Demand scenario \ Production scenario	Lower	Reference	Upper
Lower	-27%	-35%	-43%
Reference	+161%	+130%	+102%
Upper	+264%	+220%	+182%

(d) Trinidad and Tobago

Matrix comparison of the renewable potential and projected demand for selected countries in 2050. Different demand scenarios are considered in the columns and different production scenarios are considered in the rows. In each cell, the percentage of demand surplus or deficit is indicated for every production scenario relative to each demand scenario. Green cells represent scenarios with a production surplus compared to the demand, while red cells represent scenarios with a production deficit compared to the demand. For example, in a given scenario where the demand is 100 TWh/y and the production is 70 TWh/y, the corresponding cell will be colored in red and marked as -30%.

With all these resources, it is possible to discuss the energy self-sufficiency of the BEKOJAT coun-

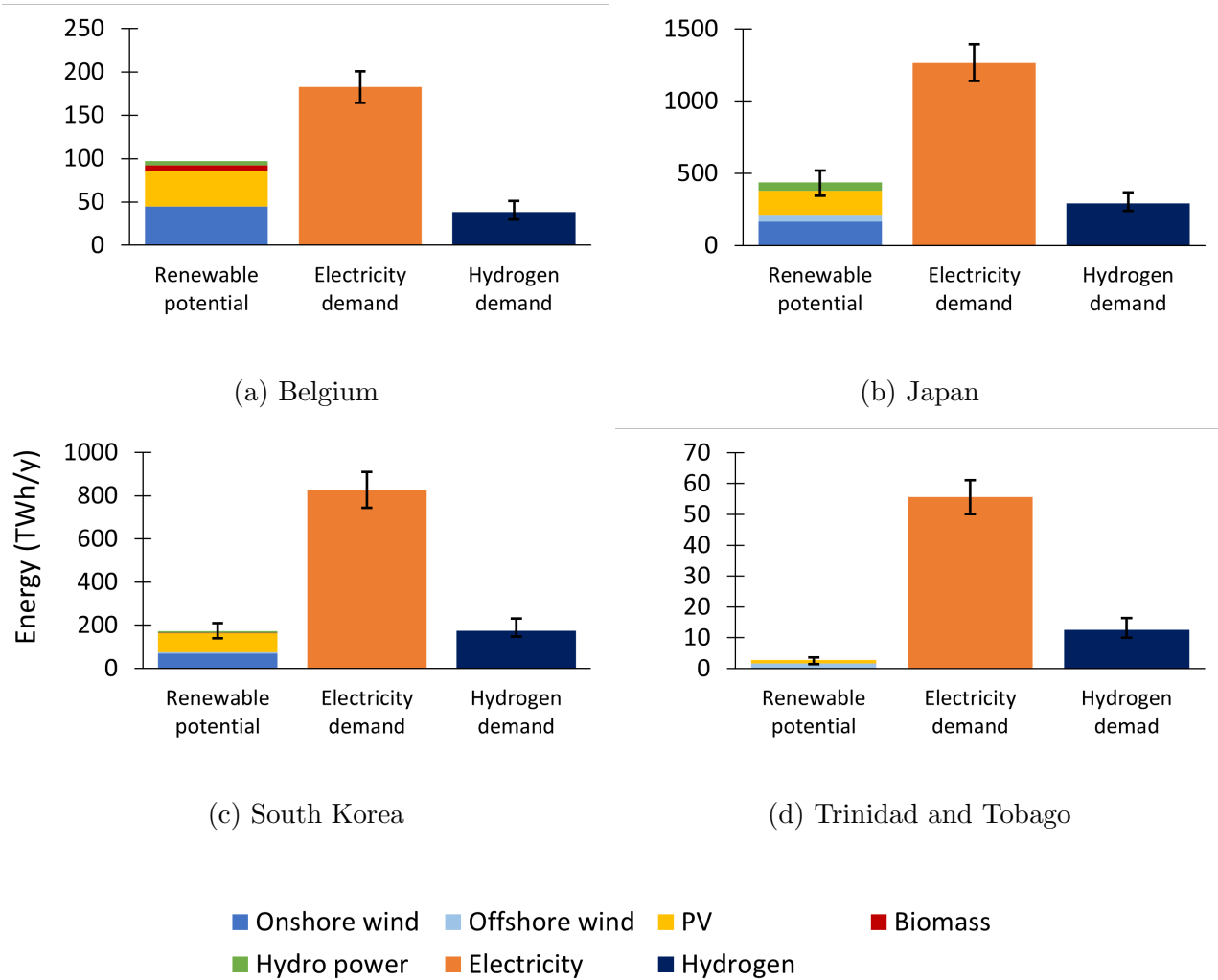
tries. Analyzing Belgium, it can be seen that the country will never be able to meet its electricity demand, which means that there will be a need to import direct electricity or hydrogen from other countries. Most of its renewable potential comes from onshore wind and photovoltaic generation, which sets Belgium apart from the other countries, whose renewable potential relies mainly on offshore wind. The fact that the country's EEZ is quite limited significantly constrains offshore wind production. Belgium also presents a peculiarity, which is its biomass potential, being the country among the four that will, in all scenarios, be able to use part of that potential to meet its electricity demand (see Table 3.2).

Concerning South Korea, in seven out of the nine scenarios, the country will not be able to meet its demand, which puts on alert the outlook of the country for the net-zero emissions scenario. The country has the second largest onshore wind and PV production among the BEKOJAT countries, but it mostly depends on its offshore wind potential to be able to be self-sufficient in the only two positive scenarios.

Japan and Trinidad and Tobago present the best outlook for the net-zero emissions scenario. In most cases, the countries would be able to meet their demand. Considering Japan, only in the worst-case scenario, where we consider a lower scenario for the production and an upper one for the demand, the country is unable to be self-sufficient. In the case of Trinidad and Tobago, in just three of the scenarios presented, the country does not meet its demand with its technical potential. However, for both countries, it is important to note that this is only possible due to their significant offshore potential. As mentioned before, Japan has an extensive EEZ, offering a technical potential approximately 4552.25 TWh/y. Trinidad and Tobago, due to its very limited land availability as a small country with a lot of protected areas (see Section 3.2), relies almost completely on its large offshore wind potential.

However, it is valuable to discuss how these scenarios would change when considering that not all the offshore wind potential will be effectively harnessed. The IEA has estimated that the technical potential for offshore wind worldwide is more than 120,000 GW, which would be enough to meet 11 times the global electricity demand in 2040 (IEA, 2019). However, due to primarily economic constraints related to the costs and challenges of offshore wind plants, the actual installed capacity predicted for 2050 by the IEA is around 1% of the worldwide technical potential. That is mainly because most of the potential is related to areas farther from the shore and in deeper waters, which significantly increases the costs (IEA, 2019). Therefore, with the goal of accounting for a more realistic analysis of the BEKOJAT countries, an outlook limiting the offshore potential contribution to the total renewable potential has to be done. Figure 3.15 and Table 3.5 displays the new scenario.

Figure 3.15: Country's Renewable Resources and 2050 Demand Projections with limited offshore production.



Comparative analysis of the renewable potential and projected electricity and hydrogen demands (TWh/y) for selected countries in 2050 when limiting the amount of offshore production according to IEA projections (IEA, 2019). Hydrogen demand is an electricity demand for producing the required hydrogen. An uncertainty of 10% was applied to the electricity demand, while the hydrogen demand uncertainty is described in Section 2.7. The different renewable sources uncertainties are thoroughly described in Chapter 2.

Table 3.5: Total annual usable renewable potential and electrical demand when limiting the offshore production.

Scenario	Total electricity production (TWh _{elec} /y)			Total electrical demand (TWh _{elec} /y)		
	Lower	Reference	Upper	Lower	Reference	Upper
Belgium	54.07	97.37	118.78	193.98	221.05	251.64
Japan	345.40	437.71	518.39	1377.52	1557.14	1761.26
South Korea	139.92	172.97	209.11	891.43	1001.28	1139.87
Trinidad and Tobago	1.38	2.72	3.55	60.02	68.19	77.51

In this scenario, none of the countries is able to meet their demand. Therefore, Japan, South Korea, and Trinidad and Tobago are no longer able to be self-sufficient under any circumstances. That result was expected since more than 90% of Japan’s and Trinidad and Tobago’s electricity production and around 75% of South Korea’s electricity production came from that source. Under these circumstances, there will be a need to import the deficit in electricity to fulfill these countries’ needs. With these results, we can analyze their national plans and some measurements that should be taken to guarantee a safe future for these nations.

3.4 Discussion

Considering Belgium’s national plan (see Section 1.2.1) and results of this study, we can see that the set targets must not only be met but surpassed. This is especially crucial for Belgium, as the country cannot achieve a net-zero emissions scenario by relying solely on its renewable resources. The offshore wind production of Belgium has been a topic of a lot of interest, including of many researches. In (Limpens and Jeanmart, 2018), the estimated offshore wind production is of 3.5 GW with an average capacity factor of 40%, which gives an approximated energy output of 12.26 TWh, a similar value to the one obtained in our study.

For Japan, a comparison can be drawn between the obtained results and the Sixth Strategic Energy Plan outlined in Section 1.2.2. While the plan aimed for a 37% contribution to the power supply, our study indicates that to achieve a net-zero emissions scenario, 65% of the demand should be fulfilled by renewables. The results also underscore the enormous offshore wind technical potential in Japan, emphasizing the need for further advancements in that domain.

South Korea, whose national plan is discussed in 1.2.3, has set the goal of 30-35% renewable energy generation by 2040. Nevertheless, in order to meet a net-zero emissions scenario, the country would have to invest more heavily in this transition, taking advantage primarily of its offshore potential. The country already has ambitious targets for its hydrogen environment which can be very positive for the future of the country, not only in terms of its industries but also in terms of creating a network that allows the country to supply its demand with hydrogen imports.

Trinidad and Tobago, as mentioned before (Jupiter and van Meurs, 2021), presents an urgency to create policies to guarantee not only the country’s energy sufficiency but also the country’s economical needs, considering the results obtained from Table 3.5. By the year 2050, all power generation should transition to renewable sources. In the face of declining natural gas production

and with significant renewable production, it is imperative that priority is given to developing the renewable ammonia, methanol and cement industries, also via tax incentives. Furthermore, the current subsidization of electricity should be phased out, leading to a necessary adjustment of electricity tariffs to reflect the true cost of power generation. To ensure a smooth transition of the power sector to sustainable practices, a national strategy must be implemented, supported by legislation that can address the short-term economic challenges that may arise.

An interesting question arises: “Given the significant impact of offshore wind potential on the overall renewable potential, what portion of the technical potential of this technology enables countries to fulfill their demand without resorting to imports?”. The results are presented in Table 3.6.

Table 3.6: Portion of the offshore wind technical potential needed to meet the demand in the reference case, per country.

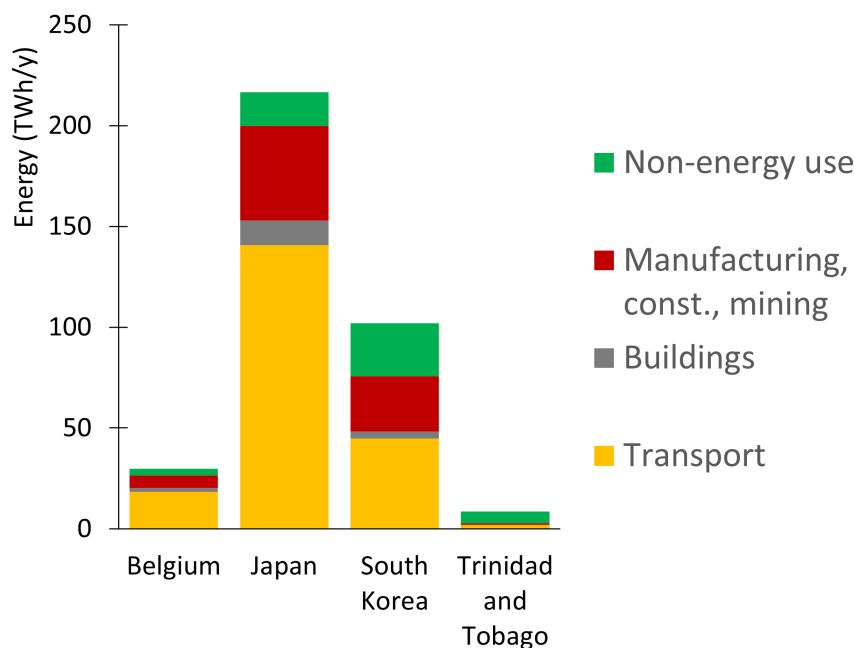
Country	Portion of the offshore wind technical potential
Belgium	1037%
Japan	26%
South Korea	146%
Trinidad and Tobago	43%

We can see that Belgium and South Korea do not have enough offshore potential to meet their demand, while Japan with around one quarter of its potential, could fulfil their energy gap. In the case of Belgium, it has been studied the possibility to acquire additional access to large offshore wind zones in the North Sea as of 2030, which could significantly increase the total potential available for the country (EnergyVille, 2023).

3.4.1 Hydrogen demand

In this section, we discuss further the deployment of hydrogen. Figure 3.16 shows how the hydrogen demand is divided between different sectors.

Figure 3.16: Country's hydrogen demand in 2050.



Comparative analysis of hydrogen demand projected in 2050 in terms of sectors. The energy is expressed in terms of electricity demand for hydrogen production (TWh_{elec}/y)

Japan, Belgium, and South Korea display similar shares between sectors, with transport being the main consumer. The transport sector is composed of rail, road, aviation, and maritime shipping. Rail transport, mainly electrified, sees limited hydrogen application, used only in non-electrified lines. Road transport, the largest segment in the sector, is divided into light-duty and heavy-duty categories. Light-duty vehicles, like cars and city buses, have seen limited adoption of hydrogen fuel cell electric vehicles (FCEVs) due to the rising popularity of electric vehicles (EVs) and insufficient hydrogen infrastructure (Plötz, 2022). According to the IEA, on the other hand, heavy-duty road transport, including long-haul trucks and coaches, presents a more favorable case for hydrogen use (IEA, 2021). Hydrogen fuel cells provide scalable power and energy, making them suitable for larger vehicles that require longer ranges and quicker refueling compared to lithium-ion batteries. However, the development of hydrogen-powered heavy-duty vehicles is still in its early stages, trailing behind the advancements seen in light-duty electric vehicles. Aviation, with high power and energy requirements, faces challenges in full decarbonization. The IRENA suggests that electrification would be possible for short-haul flights, but the majority of the demand would come from Sustainable Aviation Fuels (SAFs) (IRENA, 2021), which are biofuels used to power aircraft that have similar properties to conventional jet fuel but with a smaller carbon footprint. Maritime shipping, ultimately, another major emissions contributor, is exploring hydrogen and hydrogen-derived fuels (IRENA, 2021), such as ammonia and synthetic methane, for decarbonization, given the limitations of electrification in this sector. Therefore, the shift towards hydrogen and low-carbon technologies in the transport sector has seen significant progress and it is essential for achieving the net-zero emissions.

Following transport, the second largest sectors for these three countries are manufacturing, construction, and mining. The main industries where hydrogen can be employed are cement, steel, light industry, and refineries. In the steel industry, hydrogen is being explored as a reducing agent to replace traditional carbon-intensive processes. The main methods of steel production include the Blast Furnace-Basic Oxygen Furnace (BF-BOF) process, where hydrogen can partially replace coke or charcoal, and the Direct Iron Reduction (DRI) process, which uses hydrogen from natural gas reforming (Kim et al., 2022). The cement industry, contributing significantly to global emissions, uses hydrogen to decrease emissions from fuel combustion during production (IEA, 2018b). Next, the term 'light industry' encompasses sectors like aluminum, paper, vehicles, machinery, food, timber, and textiles, which require high-temperature heat in their processes. Hydrogen's role in these industries is primarily to replace fossil fuels in boilers IEA (2021). Lastly, refineries, one of the major industrial users of hydrogen for impurity removal and heavy oil conversion, might see a decrease in hydrogen demand as the reliance on fossil fuels diminishes (Tonelli et al., 2023).

The third largest sector for Belgium, Japan, and South Korea is the non-energy use (described in Section 3.1.1) of hydrogen. The main uses of hydrogen in this sector are the production of renewable ammonia and methanol. Ammonia production, mainly for nitrogen fertilizers, heavily relies on hydrogen as a fundamental feedstock. The current production predominantly uses steam methane reforming from fossil sources, but future methods may include cleaner alternatives like water electrolysis (Ouikhalfan et al., 2022). In methanol production, hydrogen is crucial for creating various chemicals and fuels. Similar to ammonia, methanol production currently depends on natural gas reforming and coal gasification, with potential shifts to more sustainable methods (IRENA, 2018). For Trinidad and Tobago, this sector represents the largest hydrogen demand. As described in Section 1.2.4, the country depends highly on its natural gas industry and its non-energy use. For the country to keep up with its industry activity levels and not be harmed economically by the energy transition, there is an urge for an adaptation of its industries to hydrogen. The long-term consequences of not developing renewable resources and developing renewable industries, such as renewable hydrogen. ammonia and methanol could be disastrous since the current gas-based electrical generation capacity will become useless when natural gas production becomes insufficient, and the country would not have prepared for the eventual large-scale change-over to renewables (Jupiter and van Meurs, 2021).

Finally, for all the BEKOJAT countries, there is a small share of demand destined for buildings. Using hydrogen for heating residential buildings demands an electricity amount that is significantly higher than what heat pumps require, significantly affecting monthly expenses (Altermatt, 2023). Consequently, the overall system cost associated with hydrogen heating would be approximately double that of heat pumps. Therefore, the hydrogen for this sector should be focused on larger buildings, usually commercial facilities e.g. hotels, offices, catering, shops, and institutional buildings, e.g. schools, hospitals, and offices.

3.4.2 Hydrogen import

From the discussion presented, we have identified the need to import hydrogen in the case where not all offshore potential is employed, which represents a more realistic approach to evaluate the challenges these countries will face to reach a net-zero emissions scenario by 2050. In this section, we analyze the quantity of hydrogen to be imported considering the reference scenario with limited offshore potential. Table 3.7 displays the outlook for the hydrogen import of the BEKOJAT

countries.

Table 3.7: Hydrogen to be imported.

Country	Electricity deficit (TWh _{elec})	Hydrogen equivalent (TWh)	Hydrogen import (Gt)
Belgium	123.67	206.12	6.19
Japan	1119.43	1865.71	56.03
South Korea	828.31	1380.52	41.46
Trinidad and Tobago	65.47	109.11	3.28

Considering the discussion promoted in Section 1.3, it is possible to suggest a solution for these countries to fill their energy gap. For Belgium, the North Sea corridor, with hydrogen export from France and Germany, primarily, is an interesting approach for the country. The projected hydrogen network in Europe (discussed in Section 1.3.2) can provide security for Belgium to be able to meet its demand. Furthermore, due to the large interconnection between European countries, Belgium could complement its energy deficit with the direct import of power and not depend only on hydrogen (as discussed in Section 1.3.1).

In the case of South Korea and Japan, considering the hydrogen routes in the region of the Asia Pacific, a possible solution will be importing renewable hydrogen from Oceania, represented mainly by Australia, and also from Indonesia, which are both expected to be exporters of this resource. In that case, a challenge is the transport of hydrogen, since large distances will have to be traveled. Australia, for example, is more than 6000 km away from Japan, so a developed network will be necessary to overcome this.

Finally, Trinidad and Tobago has the advantage of being in a hydrogen-exporting region, being able to import this resource from close countries, such as Chile and Colombia, with shorter distances than the ones seen in between the East Asia region and exporting regions.

Chapter 4

Conclusions

The analysis conducted in this study has led to critical insights on the renewable energy potential of the BEKOJAT countries and their self-sufficiency in the net-zero emissions scenario. These countries possess varying capacities for renewable energy production, predominantly influenced by geographical and environmental factors. Except for Belgium, with its reliance on onshore wind and photovoltaic generation potential, the other countries are more heavily reliant on offshore wind. Japan and Trinidad and Tobago, in particular, demonstrate substantial offshore wind potential, crucial for their possible energy self-sufficiency.

However, achieving net-zero emissions by 2050 presents considerable challenges, particularly when considering the realistic potential of offshore wind energy utilization. As presented in Section 3.3, Belgium faces difficulties in meeting its demand across all scenarios, primarily due to its comparatively lower offshore potential. As mentioned before, the possibility of exploiting a larger area of the North Sea could present an additional solution to the country's situation. Among the four countries analyzed, Japan demonstrates the most promising outlook, by relying on offshore wind for approximately 90% of its electricity supply. South Korea achieves self-sufficiency in only two scenarios, where offshore wind plays a substantial role. Finally, Trinidad and Tobago heavily relies on offshore wind, fulfilling its demand in most of the possible scenarios.

The limitations in harnessing the full offshore wind potential, as suggested by IEA projections (IEA, 2019), indicate that countries like Japan, South Korea, and Trinidad and Tobago will not achieve self-sufficiency. This shortfall requires exploring alternatives, such as importing the deficit in electricity and hydrogen, to fulfill their energy requirements.

The role of hydrogen as a pivotal element in the transition to renewable energy systems is underscored in this study. Hydrogen's versatility across various sectors, especially in transportation, manufacturing, and non-energy uses, marks it as a critical component in reducing carbon emissions. However, the challenge lies in developing infrastructure and technologies for efficient hydrogen production, storage, and distribution, particularly in the context of large distances and international trade. The current development of this infrastructure worldwide and, especially, in Europe, poses a positive outlook for the future of the BEKOJAT countries. Belgium could benefit from the North Sea corridor and the projected hydrogen network in Europe, while South Korea and Japan might consider renewable hydrogen imports from Oceania and Southeast Asia. Trinidad and Tobago, positioned advantageously in a hydrogen-exporting region, could leverage shorter distances for hydrogen

imports from neighboring countries.

Finally, there is an urgent need for accelerated development and implementation of renewable energy technologies and infrastructures. The transition to renewable energy sources is not just a matter of environmental sustainability, but also economic and social resilience, as highlighted in the case of Trinidad and Tobago. As the world moves towards a more sustainable future, analyzing the technical potential of countries with restricted land availability offers valuable insights and directions for policymakers and industry leaders.

Appendix A

Methodology parameters

A.1 Variation in parameters do define the boundaries

		Lower	Reference	Upper
Wind onshore	Maximum power coefficient	41%	50%	59%
Wind offshore	Maximum power coefficient	41%	50%	59%
	Distance to the coast	see Appendix A.2		
PV	Design efficiency	21.5%	24.0%	26.5%
	Degradation rate	0.335%	0.360%	0.385%
	Performance rate	76%	81%	86%
	Ground cover rate	19.5%	20.0%	20.5%
CSP	Design efficiency	18.5%	21.0%	23.5%
	Degradation rate	0.175%	0.2%	0.225%
	Ground cover rate	12.8%	13%	14%
Biomass (Crop residues)	Gas turbine efficiency	30%	40%	50%
	Biomethane yields (kg CH ₄ /kg biomass VS)	0.16	0.17	0.19
Biomass (Manure)	Gas turbine efficiency	30%	40%	50%
	Biomethane yields (kg CH ₄ /kg biomass VS)	0.03	0.15	0.22
Hydrogen	Electrolysis efficiency	50%	60%	70%

A.2 Distance to the coast suitability factors

	Distance to the coast (km)	Suitability factor
Lower boundary	>50	0.25
	<= 50 and >10	0.1
	<= 10	0.04
Reference	>= 37	0.67
	<37 and >= 9.26	0.33
	<9.26	0.1
Upper boundary	>= 37	0.77
	<37 and >= 9.26	0.43
	<9.26	0.2
Any	>160	0

A.3 Suitability factors

Label	Suitability factor	
	Wind	Solar
Post-flooding or irrigated croplands (or aquatic)	0.00	0.00
Rainfed croplands	0.70	0.10
Mosaic cropland (50-70%) / vegetation (grassland/shrubland/forest) (20-50%)	0.60	0.05
Mosaic vegetation (grassland/shrubland/forest) (50-70%) / cropland (20-50%)	0.60	0.05
Closed to open (>15%) broadleaved evergreen or semi-deciduous forest (>5m)	0.10	0.00
Closed (>40%) broadleaved deciduous forest (>5m)	0.10	0.00
Open (15-40%) broadleaved deciduous forest/woodland (>5m)	0.10	0.00
Closed (>40%) needleleaved evergreen forest (>5m)	0.10	0.00
Open (15-40%) needleleaved deciduous or evergreen forest (>5m)	0.10	0.00
Closed to open (>15%) mixed broadleaved and needleleaved forest (>5m)	0.10	0.00
Mosaic forest or shrubland (50-70%) / grassland (20-50%)	0.50	0.05
Mosaic grassland (50-70%) / forest or shrubland (20-50%)	0.50	0.05
Closed to open (>15%) shrubland (<5m)	0.50	0.10
Closed to open (>15%) herbaceous vegetation	0.90	0.10
Sparse (<15%) vegetation	0.90	0.10
Closed to open (>15%) broadleaved forest regularly flooded	0.00	0.00
Closed (>40%) broadleaved forest or shrubland permanently flooded	0.00	0.00
Closed to open (>15%) grassland or woody vegetation	0.00	0.00
Artificial surfaces and associated areas (Urban areas >50%)	0.00	0.00
Bare areas	0.90	0.10
Water bodies	0.00	0.00
Permanent snow and ice	0.00	0.00
No data (burnt areas, clouds,...)	0.00	0.00

A.4 Wind capacity factor

Figure A.1: Wind capacity fator per offshore grid cell in Belgium.

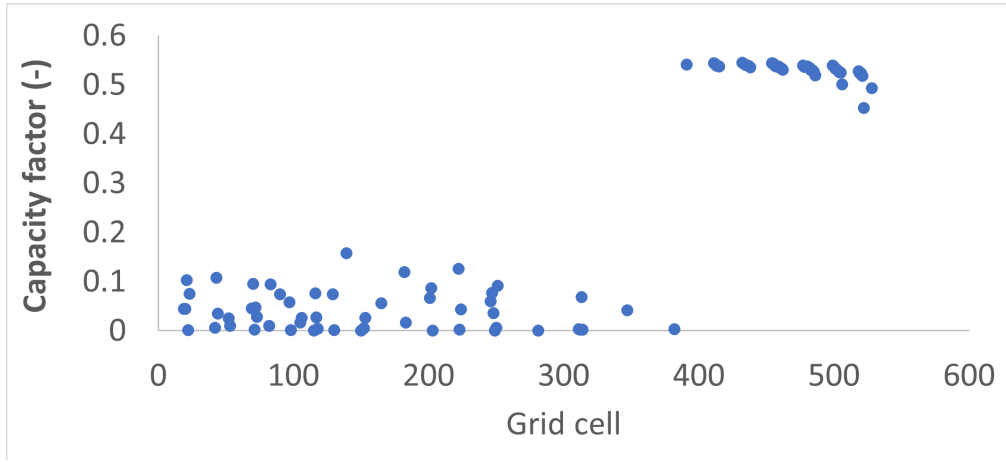


Figure displays the wind capacity factor per offshore grid cell in Belgium.

A.5 Calculation of biomethane yields from manure in Belgium with weighted averages

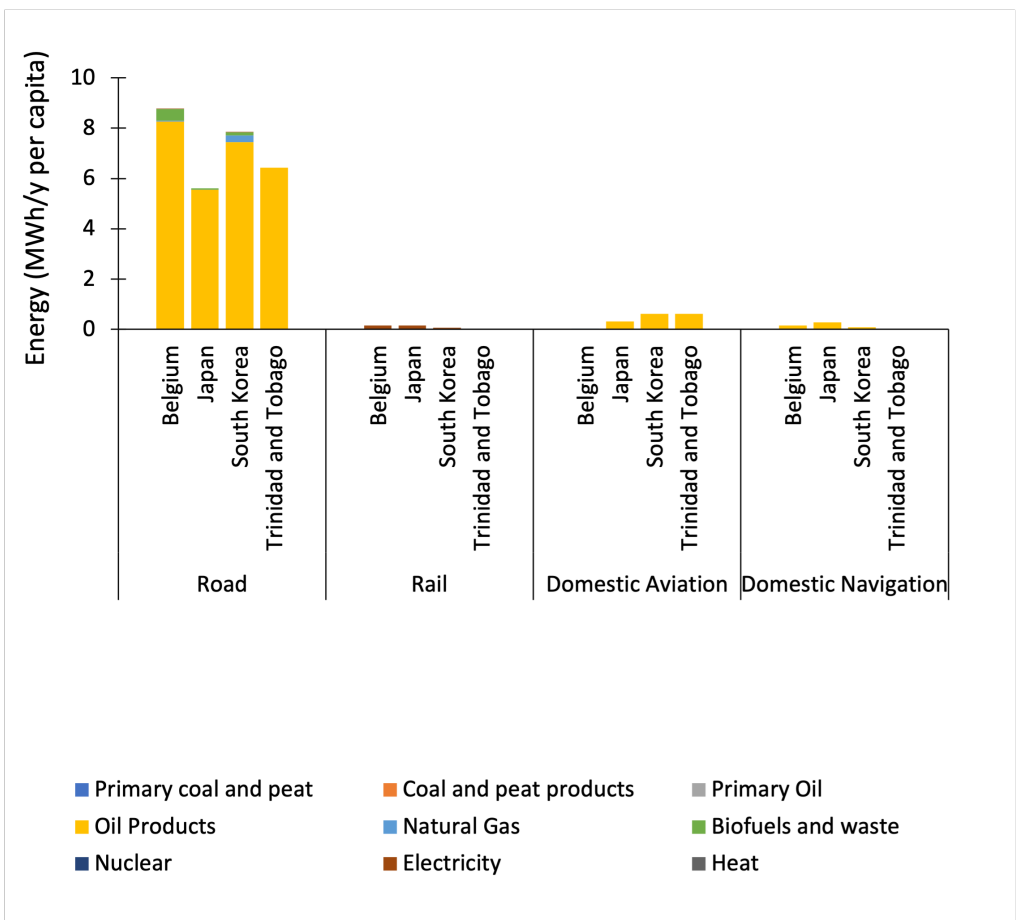
	Cattle	Pigs	Sheep/goats	Poultry	Livestock
Population (thousand heads)	2534	6477	154	34230	43395
Percentage of the population	6%	15%	0%	79%	100%
Biomethane yields ($\text{m}^3/\text{ton}_{VS}$)	230	300	200	320	-
Biomethane yields (kg/kg_{VS})	0.15	0.20	0.13	0.21	-
Weighted biomethane yields (kg/kg_{VS})	0.01	0.03	0.00	0.17	0.21

Appendix B

Results extra Figures

B.1 Transport

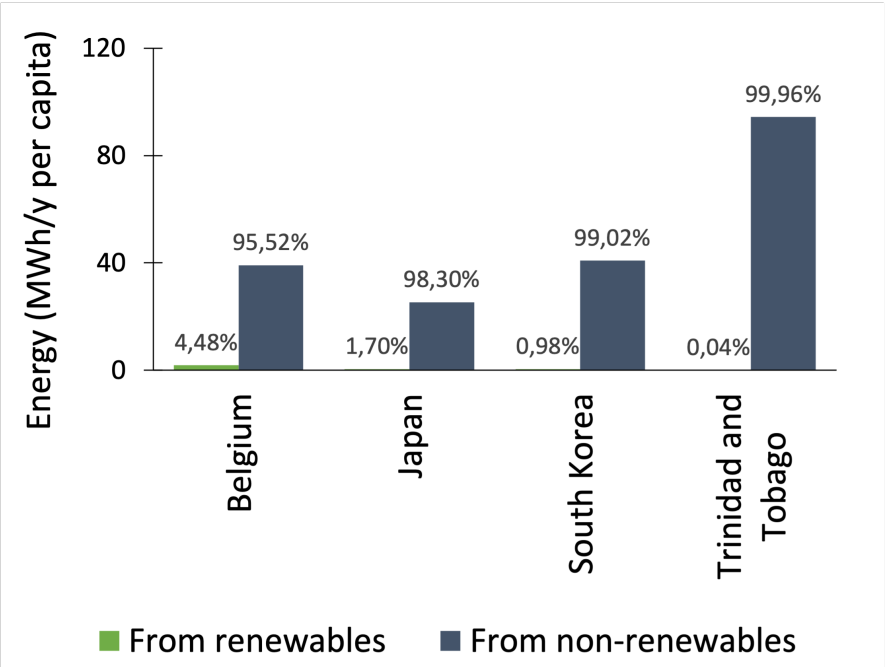
Figure B.1: Country transport per capita in 2019.



Comparison of energy demand per capita for transport in selected countries in 2019. The figure displays the per capita energy demand for transport of each country (MWh/y per capita) (United Nations, 2022).

B.2 Renewable share

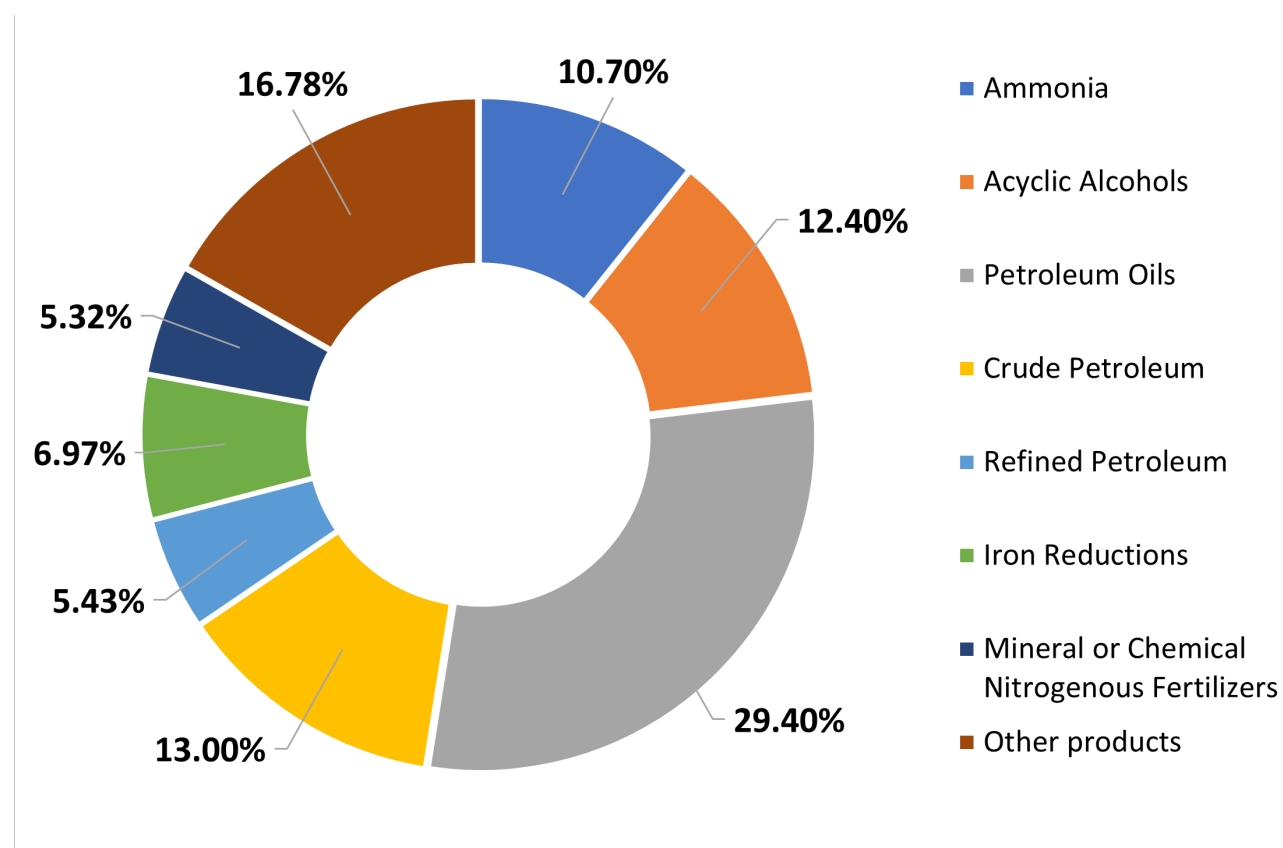
Figure B.2: Country energy consumption per capita in 2019: renewables vs. non-renewables.



Comparison of the share of energy consumption that is supplied by renewable sources and non-renewable sources. The figure displays the per capita energy balance percentage for each country.

B.3 Trinidad and Tobago exports

Figure B.3: Trinidad and Tobago export products share in 2019.



B.4 Installed capacity of wind and solar generation

Technology and scenario for renewable potential (GW)		Belgium	Japan	South Korea	Trinidad and Tobago
Wind onshore	Lower	16.57	96.56	43.78	0.17
	Reference	20.21	117.75	53.39	0.21
	Upper	23.85	138.95	62.99	0.25
Wind offshore	Lower	8.53	553.50	98.11	29.27
	Reference	33.09	1961.78	345.20	104.57
	Upper	47.64	2722.55	482.01	145.48
PV	Lower	107.02	186.97	90.15	2.43
	Reference	122.53	214.06	103.22	2.78
	Upper	138.68	242.26	116.82	3.15
CSP	Lower	2.75	3.39	1.39	0.06
	Reference	3.60	4.00	1.74	0.07
	Upper	3.89	4.63	2.01	0.08

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