NEDERLANDSE VERENIGING DUURZAME ENERGIE

A Complete Useful Energy Balance for the Netherlands

Electrons, Molecules and the Case for Electrification

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Explanatory note

During April to June 2026, the Netherlands Association for Renewable Energy (NVDE) cooperated with five second-semester students on the Utrecht University Sustainable Development Masters course, for a ten-week 'consultancy project' as part of their study programme. During this project, they worked on our request to create a 'useful energy' balance for the Netherlands, developed the required calculation tool and produced this report.

Although this type of student reports is not published externally by Utrecht University, its quality and relevance is such that NVDE, Utrecht University and the students have agreed to have it published as an NVDE report. It has been entirely produced by the students, as editors we have only replaced the Utecht University pay-off by an NVDE logo and inserted this explanatory note.

We would like to compliment the authors for the quality of the report they have produced, and thank them for a pleasant and inspiring cooperation. And we would like to thank Or Gindi and prof. Floor van der Hilst of Utrecht University for their supervision and for kindly allowing us to publish this work.

The editors

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The authors

Executive Summary

The purpose of any energy system is not to supply fuel or electricity for its own sake, but to deliver useful services like heat, light, motion. Yet the Netherlands' national energy statistics, like those of most countries, stop at final energy and never report this final stage. As a result, the current Dutch debate over the future energy mix, often framed as a contest between "electrons" and "molecules", is conducted without information on what each carrier delivers at the point of use.

This report, produced for the Nederlandse Vereniging Duurzame Energie (NVDE), closes that gap. Drawing on the JRC-IDEES dataset, we restructure its energy statistics into a single, transparent picture of how energy flows from primary through final to useful energy across the whole Dutch economy. JRC-IDEES does not report useful energy for transport, so we derive it separately with a bottom-up, device-level method, producing the first complete, all-sector useful-energy balance for the Netherlands.

The balance shows that the Dutch energy system converts only 41% of its primary energy into useful energy, and that these losses fall unevenly across carriers. At the point of use, electricity reaches the consumer at roughly 87% efficiency, fuels at only about 50%. This end-use advantage is real, but on today's fossil-heavy mix much of it is paid back upstream: a large share of electricity is generated by burning molecules at only around 39% efficiency. The two effects nearly cancel, so electricity accounts for almost the same share at both ends of the chain; about 35% of primary energy and 34% of useful energy. Where the useful-energy lens does change the picture is at the final-energy stage: electricity makes up only about a quarter of final energy but delivers a third of useful energy. Final-energy statistics, which weight carriers by energy delivered rather than service performed, therefore understate what electricity already does at the point of use.

We then use the balance to ask what happens when key sectors are electrified while the useful energy delivered is held constant. Across industry, buildings and transport, electrification delivers the same services with substantially less final energy and somewhat less primary energy. Two cross-sectoral scenarios make the decisive point: electrifying end uses cuts primary energy by about a quarter, but on the 2023 fossil-heavy generation mix that is where the gain stops. Cleaning up the electricity supply adds a further reduction of comparable size, roughly doubling the total primary-energy saving. The two levers are complementary: end-use electrification and a cleaner generation mix each capture only part of the potential primary-energy savings, and reach their full effect only in combination.

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1. Introduction

1.1. Societal Background

Through the Dutch Climate Act (Klimaatwet) the Netherlands has committed to reducing greenhouse gas (GHG) emissions in line with its international and regional commitments (Dutch government, n.D.; Regulation (EU) 2021/1119). As a key contributor to GHG emissions, there is significant focus on transitioning the energy system away from fossil fuels. Currently however, the details of what such a transition pathway would entail for the Dutch energy system remain scientifically and politically contested (Scheepers et al., 2022).

One key point of contestation is the ongoing debate over the role of different energy carriers in the post-transition energy mix, sometimes framed as a battle between advocates of 'electrons' and 'molecules' (Ember, 2026). Currently, actors within this debate can only rely on primary, secondary, and final energy statistics to inform their arguments and recommendations to stakeholders and policy makers, which impacts the landscape of such debates (Rodriguez et al., 2020).

While these statistics are helpful in certain types of analysis, they to somewhat obscure the true purpose of the energy system; to transform energy into a form which can be used to provide useful services (Fell, 2017). As such, the energy system can be viewed as a chain of transformations: an initial raw commodity (crude oil, for example) is extracted, transformed (i.e. refined and converted into petrol), transported to a consumer, and then finally converted by an end-use device into a useful form (transformed into kinetic energy by a car engine). The last stage of this conversion chain is useful energy, a metric denoting the specific fraction of energy that actively contributes to the desired output. It constitutes the effective energy applied to perform a specific function, such as generating thermal heat, providing lighting, or producing mechanical power (Cleveland & Morris, 2015).

Currently however there are no robust and comprehensive sector-wide useful energy statistics for the Dutch context. Worldwide, this phenomenon has led to an underestimation of the already existing role of electricity as an energy carrier (Ember, 2026; Ritchie, 2022). Thus, it imperative for methods of calculating useful energy to be developed so political actors, armed with more complete information can make better decision regarding the Dutch energy transition.

1.2. Scientific Background

1.2.1. Energy Statistics

Traditionally, national energy balance reports do not include useful energy statistics. Useful energy is not included in the *Energy Statistics Manual* produced by the IEA, which attempts to harmonize the collection of national energy statistics worldwide (OECD/IEA, 2004). This is often due to the heterogeneity in the efficiencies of specific technologies and conversion process globally a contributing factor in the global norm, including for the Netherlands of not reporting these values.

The concept of useful energy, however, has long been discussed and defined in academic literature. The process of energy transformation from extraction of natural resources to their ultimate end-use application can be systematically categorized into four sequential stages: primary, secondary, final, and useful energy (Figure 1).

The sequence originates with primary energy: energy commodities that are either extracted or captured directly from natural resources (OECD/IEA, 2004). This category encompasses unrefined resources such as crude oil, coal, biomass, and geothermal heat, secondary energy refers to commodities that have been transformed in some way, through either one or more conversion processes (Ritchie, 2022). Following transmission and distribution, which incur additional systemic losses along grids and pipelines, the energy delivered to the end consumer is classified as final energy. This term functions as an aggregate designation for the various forms of energy sold to and utilized by ultimate consumers, including residential households and industrial facilities (Cleveland & Morris, 2015).

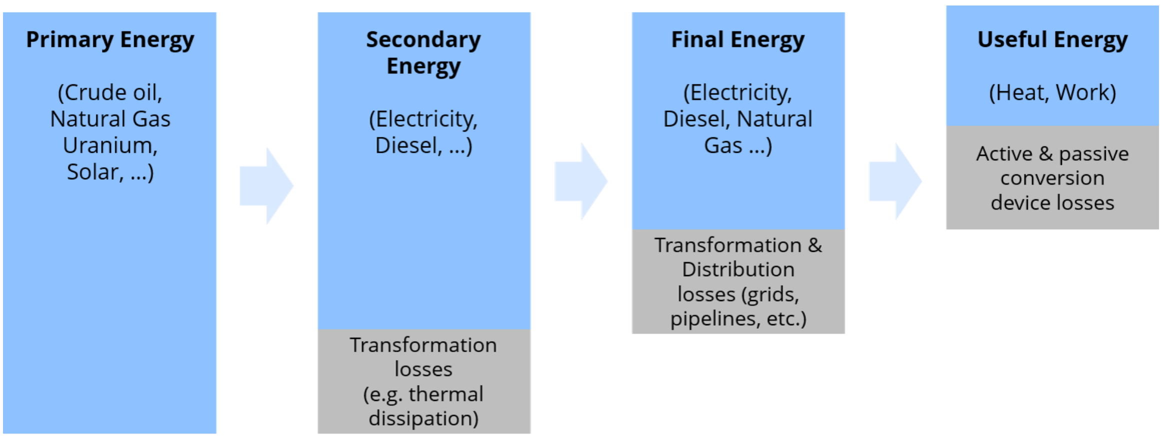


Figure 1: The Conversion from Primary Energy to Useful Energy Including Losses Due to Inefficiency (Ritchie, 2022).

1.2.2. Useful Energy Calculations

Historically there have been several attempts to calculate and report useful energy statistics and regional and global levels. Of these existing studies, the most widely used is the Primary, Final and Useful Energy Database (PFUDB) dataset constructed by IIASA (de Stercke, 2014). This database compiles an extensive set of useful energy estimates made across 20 countries or geographic groups, dating from 1947 to 2014. The study then uses these place- and time-specific estimates to derive a set of general expressions. However, the age, aggregated nature of the data and derivation of efficiency values from GDP data creates large uncertainty in the results, limiting their applicability to national level policy making.

Paoli et al. (2018) developed a framework to calculate useful energy balances in the UK for a single year. Drawing on statistics provided by the UK government and industry bodies, Paoli et al. allocate final energy consumption by sector and fuel carrier into 9 generalised end-use categories according to an allocation matrix (φ), and then again according to the type of conversion device used. Multiplying each of these disaggregated shares by the specific efficiency of said device gives a value for useful energy.

Lastly, the Joint Research Centre's Integrated Database of the European Energy System (JRC-IDEES) provides a dataset that includes useful energy reporting at the member state level, which includes the Netherlands (Rózsai et al., 2026). The conversion efficiencies from final to useful energy within JRC-IDEES are modelled based on European averages. While this generalized approach is highly sophisticated and often represents the best available baseline, it fails to capture country-specific operational realities. For example, it misses unique features of the Dutch energy system like the widespread use of Combined Heat and Power (CHP) units in the agricultural sector to simultaneously heat greenhouses and generate electricity. Furthermore, it is important to note that this data is not available for all sectors, as information on the transport sector is missing (Rózsai et al., 2026).

This leads to a clear research gap: there is currently no complete useful energy balance that accounts for the unique Dutch characteristics and covers all sectors. Consequently, there is a lack of scenario modelling which optimises the Dutch energy system from a useful energy perspective. Without such scenarios, it remains unexplored how the Netherlands can deliver the same amount of useful energy while significantly reducing its primary energy input.

1.3. Research Aim and Question

The primary objectives of this study are to develop a comprehensive, all-sector national useful energy balance sheet for the Netherlands, and then to explore some illustrative (or “What-If”) scenarios through this lens of useful energy.

To achieve this, we developed a fully transparent tool that calculates useful energy statistics from final energy balances. The transparent data sources and methodology mean this tool can be further developed by NVDE and will continue to impact Dutch energy debates.

Utilizing this tool, we hold useful energy constant and explore a series of What-If scenarios which jointly illustrate the systemic impact of widespread electrification.

These will be used by NVDE to communicate with policymakers and the public in energy policy debates.

This study therefore addressed the following core question (CQ1) and 4 sub-questions (SQ1-4):

CQ1: *How does the lens of useful energy shed new light on the relative importance of different energy carriers in the Dutch energy system?*

SQ1*: How can a transparent, all-sector useful-energy balance for the Netherlands be derived from existing final-energy data; including the sectors not covered by JRC-IDEES (transport)?*

SQ2: *How is the Netherlands' useful energy in 2023 distributed across sectors and energy carriers, and how does the conversion efficiency of electricity and molecules differ along the primary–final–useful energy cascade?*

SQ3*: How do final and primary energy demand change when industry, the built environment, and road transport are switched to electricity- or hydrogen-based technologies while useful energy is held constant?*

SQ4: *To what extent do the primary-energy savings of a highly electrified system depend on the underlying electricity mix?*

2. Methods

2.1. Useful Energy Balance

Whilst the conceptual framework developed by Paoli et. al (2018) is suitable and was highlighted as our preferred option in the research proposal, we found after beginning the analysis that the lack of sufficiently detailed industrial data for the Dutch context meant that replicating the Paoli et al. (2018) method would have introduced a high degree of uncertainty.

We therefore used the JRC-IDEES dataset as the foundation for this study, restructuring the data into a usable format and then appending the missing transport sector using the method established by Paoli et al. (2018). The dataset is tailored where necessary to account for the specific characteristics of the Dutch energy system. In the following section, the primary data sources and the underlying JRC-IDEES methodology are briefly explained, followed by a detailed description of our data processing strategy and the methodology used to enrich the dataset by incorporating the transport sector.

2.1.1. Data Sources

The core dataset used for this project is the JRC-IDEES, which compiles and processes energy statistics for EU member states, including the Netherlands. Unlike the methodology used in Paoli et. al (2018) JRC-IDEES decomposes sectoral final energy consumption into sub-sector-specific end-use categories rather than standardized end-use and conversion device categories (Rózsai et. al, 2026).

The database decomposes energy balances into the following sectors, with each sector treated slightly differently: industry residential, tertiary and agriculture, transport, and power & heat generation. The industry sector is decomposed into sub-sectors, with statistics on physical sectoral output (e.g. tonnes of raw steel production) combined with economic and reference energy intensities of material production to calculate sub-sector level useful energies (Rózsai et. al, 2026).

2.1.2. Data Processing & Sectoral Calibration

JRC-IDEES is used as the direct source for the sectors in which it provides both final-energy consumption and useful-energy demand; the Eurostat-consistent energy-balance file (within the same dataset) is used as the calibration anchor for the residential and services sectors and as the direct source for feedstock, energy-sector own use and distribution losses; and the Paoli-style decomposition is applied only to the transport sector, for which JRC-IDEES does not publish a useful-energy demand. Appendix III summarises the source, calibration and decomposition applied per sector, together with the Dutch-specific corrections introduced in this study.

The static energy balance computes the useful energy for every row as Useful = Final × Share × η (Final → Useful), where the end-use shares within each (subsector, fuel) sum to unity so that the final energy is allocated across end uses without double counting. The detailed equation applied to the transport sector is given in 2.1.3 (Equation 1). For each industrial subsector the final energy is obtained by aggregating the process-level final-energy consumption reported in the JRC-IDEES subsector sheets (Rózsai et al., 2026). The aggregation traverses the hierarchical structure of each sheet using the cell indentation, summing only at the leaf level so that parent totals are not counted together with their components. For each (subsector, fuel, end use) the share is defined as the process final energy divided by the total final energy of that (subsector, fuel), and the efficiency as the useful energy demand divided by the final energy of the same process.

The JRC processes are grouped into distinct end use buckets. These include nonthermal applications such as motors and lighting, as well as cooling. To structure the analysis of the thermal processes, the various heat related end use categories from the JRC Energy Balance, which form the basis of the useful energy balance, were aggregated into three specific heat categories, drawing on the industrial expertise of the NVDE. The first category is low temperature heat, which is supplied as warm air or hot water. The second category, medium temperature process heat, encompasses process steam at approximately 150 to 450 °C and is primarily utilized in the chemical, food, paper, and textile industries, as well as for drying processes. The third category covers high temperature process heat required in furnaces, kilns, smelters, ovens, and melting tanks operating above 450 °C. The exact division is shown in Appendix IV. With this construction, the modelled industrial final energy reproduces the JRC industry total of 487.2 PJ, and the modelled industrial useful energy reproduces the JRC useful energy demand of 273.3 PJ.

For the residential, services and agriculture sectors, the final energy by fuel is taken directly from the Eurostat-consistent rows of the JRC energy-balance file. The end-use shares and conversion efficiencies are retained from the JRC residential and tertiary sub-models. The non-renewable waste in services is grouped with biomass and renewables. This calibration corrects a small biomass undercount present in the original JRC sub-models relative to the official energy balance, of approximately 17 PJ for the residential sector and 13 PJ for the services sector.

Industrial non-energy use, which for the Netherlands consists primarily of oil products and natural gas employed as raw material in the chemical industry, is represented as a separate block with an efficiency of 100%, in keeping with the convention that the energy content is retained in the product (Daioglou et al., 2014). For the Netherlands in 2023 this amount to 432.2 PJ, of which 365.2 PJ are oil products and 67.0 PJ are natural gas.

Refineries, power plants, coke ovens, blast furnaces and oil-and-gas extraction installations consume energy themselves while transforming primary into final energy. The Eurostat balance reports this on a dedicated line ('Energy sector own use', 191.5 PJ for the Netherlands in 2023). Distribution losses (25.8 PJ) are reported on a comparable memo line. Both categories are included as separate sectors in the balance workbook, with the fuel-level breakdown taken directly from the JRC energy-balance file. These rows carry an efficiency of zero, so they contribute to final and primary energy without inflating useful energy. Including them permits reconciliation of the model's primary energy with the Dutch Gross Inland Consumption (Rózsai et al., 2026).

Two dedicated reconciliation sheets compare the modelled totals against external references. The first compares the modelled final energy in every subsector against the Eurostat-consistent figure of the JRC energy-balance file; after the calibration of the residential and services biomass figures, all 18 subsectors and every sector total agree within rounding. The second compares the modelled useful energy against the JRC useful-energy demand for industry and agriculture, where it is published; for the residential, services and transport sectors, no directly comparable JRC figure is available, and this is documented on the sheet.

2.1.3. Enriching the Dataset: Transport Sector

Because the JRC-IDEES database does not publish a useful-energy balance for the transport sector, these values must be derived device by device. To calculate the useful energy for transport, a decomposition method proposed by Paoli et al. (2018) is applied. In this framework, a bottom-up approach signifies that the total useful energy is not estimated at a macro level, but is instead aggregated from the lowest tier of individual end-use devices. The formula is summarized in Equation 1.

Equation 1: Useful energy as a function of different conversion devices disaggregated by end-use category, fuel source, and sector (Source: Paoli et. al 2018).

$$U = \sum U_{f,s} = \sum F_{f,s} \times \varphi_{f,s,d} \times \theta_{f,s,d} \times \eta_{f,s,d}$$

Where:

U = useful energy

$U_{f,s}$= useful energy of fuel (f) in sector (s)

$F_{f,s}$= final energy consumption of fuel (f) in sector (s)

$\varphi_{f,s,d}$= end-use allocation matrix (here only mechanical motion)

$\theta_{f,s,d}$= market share of different devices (d) using fuel (f) in sector (s)

$\eta_{f,s,d}$= conversion efficiency of different devices (d) using fuel (f) in sector (s)

Following this mathematical logic, rather than analyzing the final energy consumption of the transport sector as a single entity, the data is further disaggregated by specific energy carriers and end use devices. Specifically, the analysis categorizes the sector into gasoline engines, diesel oil engines, LPG engines, natural gas engines, and battery electric motors.

To determine the exact technical performance of these technologies, a literature review was conducted to obtain tank to wheels (TTW) efficiency data for the different motor types, representing the precise percentage of energy successfully converted into useful work. The useful energy is then calculated separately for every vehicle and fuel combination. This is achieved by calculating a weighted average of the TTW efficiencies based on the respective market shares of the deployed motors, thereby establishing the accurate useful energy efficiency for each energy carrier.

Finally, all these individual outcomes are summed up to determine the total useful energy for the entire sector. The useful energy efficiencies used in the scenario model and the corresponding data sources are presented in Appendix I and Appendix II.

2.2. What-If Scenarios

As the next step of the analysis, a series of What-If scenarios are introduced to explore how different technology and policy choices affect the Dutch primary-to-useful energy cascade. Specifically, these scenarios evaluate how the required primary energy input shifts when the exact same amount of useful energy is delivered through alternative energy carriers and technologies. By holding useful energy constant, this aligns with the recommendations by Ember (2026) to analyse and plan the energy system based on useful energy demand. The developed scenarios explore the impact of low-carbon technologies on primary energy consumption across different sectors. Additionally, they investigate the systemic consequences of an insufficient decarbonization of the electricity grid under a pathway of rapid, high-level electrification.

The following What-If Scenarios were developed in collaboration with NVDE.

Table 1: Summary of Developed What-If Scenarios.

Sector	**Scenario Name**	**Targeted End-Use**	**System & Technology Focus**
Industry	*Electrify & H_2*	Industrial Heat	Industrial Heat Pumps; Electric Boilers; Hydrogen Boilers
	NG CCS		Natural Gas with CCS
Built Environment	*Heat Pump*	Space Heating; Water Heating	Electric Heat Pumps
	District Heating		District Heating

<table>
<tr><th>Sector</th><th>Scenario Name</th><th>Targeted End-Use</th><th>System & Technology Focus</th></tr>
<tr><td rowspan="2">Transport (Road)</td><td>Mid-EV</td><td rowspan="2">Mechanical motion</td><td>Battery Electric Vehicles</td></tr>
<tr><td>Deep-EV</td><td>Battery Electric Vehicles</td></tr>
<tr><td rowspan="2">Cross-Sectoral</td><td>Electrify Only</td><td>Industrial Heat; Space Heating; Water Heating; Mechanical Motion</td><td>Industrial Heat Pumps; Electric Boilers; Hydrogen Boilers; Battery Electric Vehicles</td></tr>
<tr><td>Electrify + Clean Grid</td><td></td><td>Industrial Heat Pumps; Electric Boilers; Hydrogen Boilers; Battery Electric Vehicles + Decarbonized Power Grid</td></tr>
</table>

2.2.1. *Industry*

The industrial scenarios aim to compare various low-carbon heat generation technologies in the industrial sector against the 2023 baseline scenario. For this purpose, the "Electrify & H_2" scenario was developed, which achieves decarbonization through a combination of electrification and the deployment of hydrogen. Additionally, a fossil-retention scenario “NG CCS” was examined, in which the heat demand is met using natural gas combined with Carbon Capture and Storage (CCS).

Based on the three industrial heat categories (see 2.1.2), the Electrify & H_2 scenario was designed with specific technological constraints. Although heat pumps represent the most efficient technology, we assume that the technical application is limited to a maximum of 40 % of the total industrial heat demand, which corresponds to 60% of the low temperature heat demand. The remaining low temperature energy demand in this scenario is covered by electric boilers, given their high final to useful energy conversion efficiency. Furthermore, it is assumed that while electric boilers can adequately satisfy the medium temperature process heat demand, they are not suitable for generating high temperature process heat. Consequently, hydrogen boilers are deployed for this specific high temperature segment. For the hydrogen boilers, a primary energy factor of 0.67 was adopted from the JRC database. This indicates that the electrolysis process operates at an efficiency of 67%, requiring a proportionally higher primary energy input to generate the required final hydrogen. Furthermore, while one could theoretically account for additional efficiency losses during the generation of the electricity used for this electrolysis, this model assumes a 100% primary-to-final energy conversion efficiency. In practice, this assumption directly corresponds to sourcing the electricity from renewable technologies such as wind power.

The NG CCS scenario, however, relies on the simplified assumption that the entire useful energy demand is met exclusively using natural gas combined with carbon capture and storage (CCS). The implementation of CCS introduces an assumed energy penalty of 8%.

Finally, Table 2 illustrates the scenario design, detailing the specific share of each heat category supplied by the respective technologies, while Table 3 details the assumed technological efficiencies.

Table 2: Assumed Technology Mix by Heat Category.

Heat Category	**Useful Energy (PJ)**	**Electrify & H2**	**NG CCS**
Low-temp heat	143.5	60% Heat Pump, 40% Electric Boiler	100% NG CCS
Process heat (medium)	41.5	100% Electric Boiler	
Process heat (high)	31.8	100% Hydrogen Boiler	

Table 3: Assumed Efficiencies (Useful to Final).

Technology	**Efficiency**	**Source**
(Industrial) Heat Pump	3.28	Marina et al. (2021)
Electric Boiler	0.99	Thermona (2010)
Hydrogen Boiler	0.85	Rademaker & Marsidi (2019)
CCS - Penalty	-0.08	Zheng et al. (2023)

2.2.2. *Built Environment*

Within the built environment we explored the effect of changing how space and water are heated in buildings. The built environment encompasses residential dwellings and buildings providing commercial services. We look at two scenarios. First, we consider a switch to heat pumps for 100% of all water and space heating demand. Secondly, we consider a switch to district heating to provide the realistic maximum of space and water heating needs. These scenarios were designed to illustrate the implications of transitioning from traditional natural gas/oil boilers to commonly recommended alternatives for the built environment.

In the Heat Pump scenario, we assume an efficiency of 285% for heat pumps used for space heating and efficiency 225% for heat pumps used for water heating. The efficiency of water heating heat pumps is assumed to be lower due to their need to heat water to higher temperatures, effecting the coefficient of performance (COP). In the model, the share of heat pumps for all water and space heating demand is set to 100%. The share of all other conversion devices is set to 0%.

In the District Heating scenario, we model a 30% share of Dutch residential and commercial space heating and water heating needs to be provided by district heating systems, taking this from the realistic upper bound of domestic district heating (van Polen, 2025, pg. 18). The share is 4.2% in the NL 2023 baseline scenario. In the absence of reliable commercial district heating modelling, we assume this to follow the residential limit.

We take the share of district heating itself that is derived from geothermal and ambient/waste sources as being 70%, the most conservative value estimated by Teng et al. (2025). The remaining is assumed to be provided by other thermal sources (e.g. CHP, Boilers) and thus requiring additional primary energy.

2.2.3. *Transport*

These scenarios directly contrast the energy efficiency profiles of the national vehicle fleet. It compares a pathway of rapid, widespread electrification against a baseline scenario where cars continue to run on fossil fuels.

In addition to the baseline scenario, this report proposes moderate electrification scenario (Mid-EV) and deep electrification scenario (Deep-EV) for analysis, as shown in Table 4. The majority of electrification-related CO_2 emission reductions are in the road transport sector, specifically within the light-duty vehicle segment (IEA, 2023). Therefore, the scenario assumptions regarding the electrification of the transport sector will focus on the road sub-sector, whereas the rail and domestic navigation will remain unchanged.

In the Mid-EV scenario, it is assumed that 60% of fossil fuel (oil products and natural gas) will be replaced by electricity. Biofuels are often used as additives to gasoline and diesel. Given that oil products will still account for a certain share of use in this scenario, it is therefore assumed the share of biofuels remains unchanged.

In the Deep-EV scenario, the use of fossil fuels will be completely replaced by electricity, and the fuel mix of the road sub-sector will consist of 100% electricity.

Table 4: Assumptions of Transportation Sector.

Subsector	**Mid-EV**	**Deep-EV**
Road	60% Oil → Electricity 60% NG → Electricity Biofuels: Remain Unchanged	100% Oil → Electricity 100% NG → Electricity 100% Biofuels → Electricity
Rail	Remain Unchanged	Remain Unchanged
Domestic Navigation	Remain Unchanged	Remain Unchanged

2.2.4. *Cross-Sectoral*

The cross-sectoral scenario evaluates the impact of deep electrification against the baseline under two distinct conditions: operating with the current electricity mix versus transitioning to a projected decarbonized power grid.

The "Electrify Only" scenario represents a synthesis of the electrification pathways from the individual sector scenarios. It integrates the "Electrify & H_2" scenario for industrial heat, the "Heat Pump" scenario for space and water heating, and the "Deep-EV" scenario for road transport and mechanical motion. All other energy end-uses, which were not altered in the previous sector-specific analyses, are included in this scenario and retained at their baseline levels.

The "Electrify + Clean Grid" scenario builds directly upon the preceding scenario. The sole modification is that, rather than utilizing the baseline electricity mix, this scenario adopts the projected electricity generation mix from the "Eigen Vermogen 2050" scenario published by Netbeheer Nederland (2025). It is important to note that the adopted generation mix specifically represents the electricity supplied to the grid for direct end-uses, such as space heating and transportation. The portion of electricity dedicated to domestic hydrogen production was explicitly excluded from this grid mix. Because hydrogen is already accounted for as a distinct fuel within the model, incorporating the electricity required for its electrolysis into the general grid mix would result in the double counting of wind electricity. Both of these electricity generation mixes are detailed in Table 5.

Table 5: Electricity Generation Mix: Baseline vs Scenario.

Electricity Generation Source	Share of Generation Baseline 2023	Share of Generation Scenario EV 2050
Natural gas	39%	0%
Coal	8%	0%
Biomass (solid)	5%	3%
Nuclear	3%	8%
Wind	24%	58%
Solar PV	16%	29%
Hydrogen	0%	3%
Others	5%	0%
TOTAL	**100%**	**100%**

2.2.5. *Scenario Model*

To evaluate the developed What-If scenarios, the static energy balance is extended into a dynamic Scenario Model that captures the full cascade from primary to useful energy. The baseline values for every unique combination of sector, subsector, end-use, and fuel carrier are read directly from the main energy-balance workbook, ensuring absolute consistency between the baseline dataset and the subsequent analysis. This model is designed with a dual purpose: it establishes the methodological foundation to simulate the predefined What-If scenarios, while simultaneously serving as an interactive tool for NVDE to explore custom future pathways by independently adjusting system parameters.

For every fuel a Primary-to-Final factor is applied that captures upstream losses from extraction, refining, conversion and distribution. For electricity the factor is derived from the 2023 Dutch generation mix reported in the JRC power-generation file: the share of each generation source is divided by its conversion efficiency (renewables at 100% under the physical-energy-content convention; thermal sources between 25% and 50%), normalized by the sum of shares and corrected for grid and distribution losses. The resulting primary factor for the Netherlands is 1.84.

The structural flexibility of the scenario model relies on four adjustable parameters embedded within every row of the dataset: the Primary-to-Final efficiency, the Final-to-Useful efficiency, a demand factor, and the fuel share within an end-use group. A change in the fuel share shifts a service from one fuel to another while holding the useful energy constant. Modifications to any of these parameters propagate to the primary, final and useful totals on the results sheet of the model.

3. Results

3.1. Useful Energy Balance

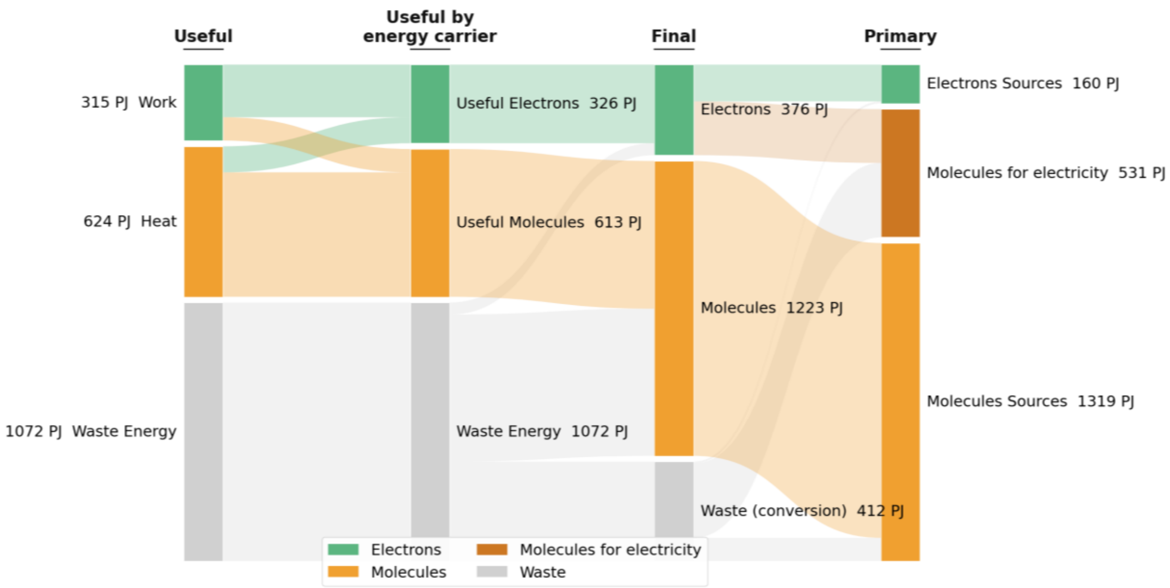


Figure 2: Energy Balance for the Netherlands in Petajoules (2023, JRC-IDEE).

Figure 2 shows the energy balance of the Netherlands for the year 2023 (in petajoules, PJ), displaying each stage of energy transformation, working backwards from useful energy (left) back to primary energy (right). The graph includes the losses at each stage and hence shows the overall conversion efficiencies from primary energy to useful energy.

The overall process has an efficiency of 41%. The efficiency losses are foremost located at two stages: first, when electricity is produced from fossil fuels 39% efficiency, and second, during the transition of molecules from final energy to useful energy, where a significant portion of waste energy is generated (50% efficiency).

Figure 2 also shows the relative shares of molecules and electrons at each stage. In the current Dutch energy balance, 34% of the useful energy consumption is furnished by electrons and 66% by molecules. It is possible to observe roughly the same ratio when looking at the need for primary energy, where practically 35% of the primary energy is used to generate electrons. However, when examining the transition from final to useful energy, we see a substantial difference, with electrons accounting for only 23.5% of the overall final energy mix.

The development of useful energy demand between the years 2000 to 2023 can be found in Appendix VI.

3.2. What-If Scenarios

3.2.1. *Industry*

Figure 3 illustrates the final and primary energy demand (in petajoules, PJ) for industrial heat under the two constructed decarbonization scenarios (Electrify & H_2 and NG CCS) compared to the 2023 Netherlands baseline (NL 2023). A constant useful heat demand of approximately 220 PJ is maintained across all cases as the reference point.

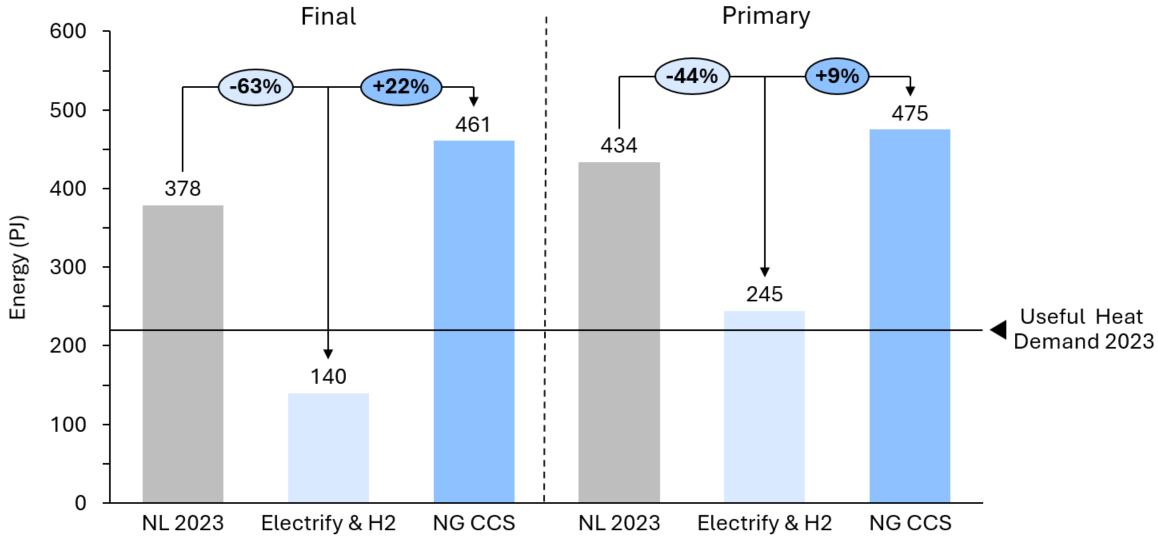


Figure 3: Industrial Heat: Decarbonization Scenarios vs. Baseline (NL 2023)

Regarding final energy, the Electrify & H_2 scenario demonstrates a substantial 63% reduction, dropping to 140 PJ from the 378 PJ baseline. In contrast, the NG CCS scenario results in a 22% increase, raising the final energy demand to 461 PJ. A similar divergence is observed in primary energy requirements. The Electrify & H2 pathway reduces primary energy demand by 44%, decreasing from 434 PJ to 245 PJ. Conversely, the NG CCS approach leads to a 9% increase, reaching a total of 475 PJ. Overall, the data highlights the significant systemic efficiency gains of the electrification and hydrogen pathway compared to the increased energy input required to maintain fossil fuel usage with carbon capture technology.

3.2.2. *Built Environment*

Figure 4 shows how final energy consumption (PJ) and primary energy (PJ) vary under the Heat Pump and District Heating scenarios.

Under the Heat Pump scenario, final energy and primary energy demand undergo significant reductions of 60% and 37% respectively.

Under the District Heating scenario, primary energy increases slightly (an increase of 1%) relative to the NL 2023 baseline, whereas final energy demand reduces slightly (a decrease of 2%). Figure 4 indicates the share of this energy which is estimated to be derived from geothermal and therefore renewable sources (78 PJ in the District Heating scenario).

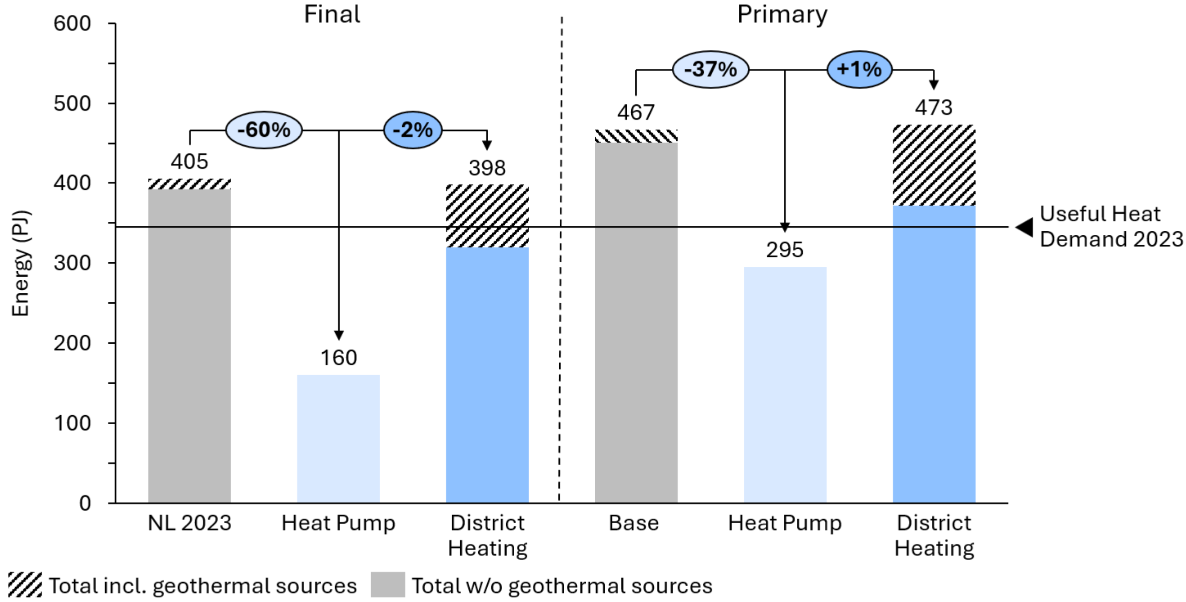


Figure 4: Space and Water heating: Heat Pumps and District Heating vs. Baseline (NL 2023).

3.2.3. Transport

The final energy and primary energy consumption of the road subsector under the baseline are compared with those under the Mid-EV and Deep-EV scenarios, ad shown in Figure 5.

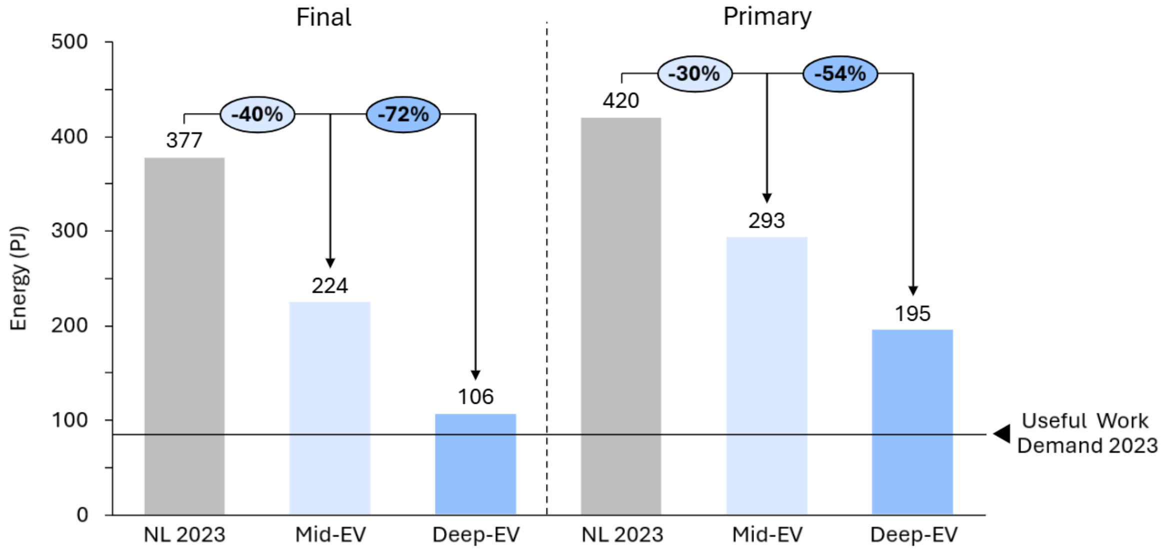


Figure 5: Road sub-sector: Moderate and Deep Scenario vs. Baseline (NL 2023).

Under the baseline scenario, the transport sector requires 92.6 PJ of useful energy, corresponding to a final energy consumption of 377 PJ. This indicates that only 25% of the final energy is converted into useful energy.

With useful energy held constant, final energy consumption decreases by 40% and 72% under the Mid-EV and Deep-EV scenarios, respectively. Although primary energy consumption also decreases significantly under both electrification scenarios, the reduction is smaller than that of final energy consumption, with decreases of 30% and 54% in the Mid-EV and Deep-EV scenarios, respectively.

3.2.4. Cross-Sectoral

Figure 6 presents the final and primary energy demand in petajoules for the cross-sectoral electrification scenarios compared to the 2023 Netherlands baseline.

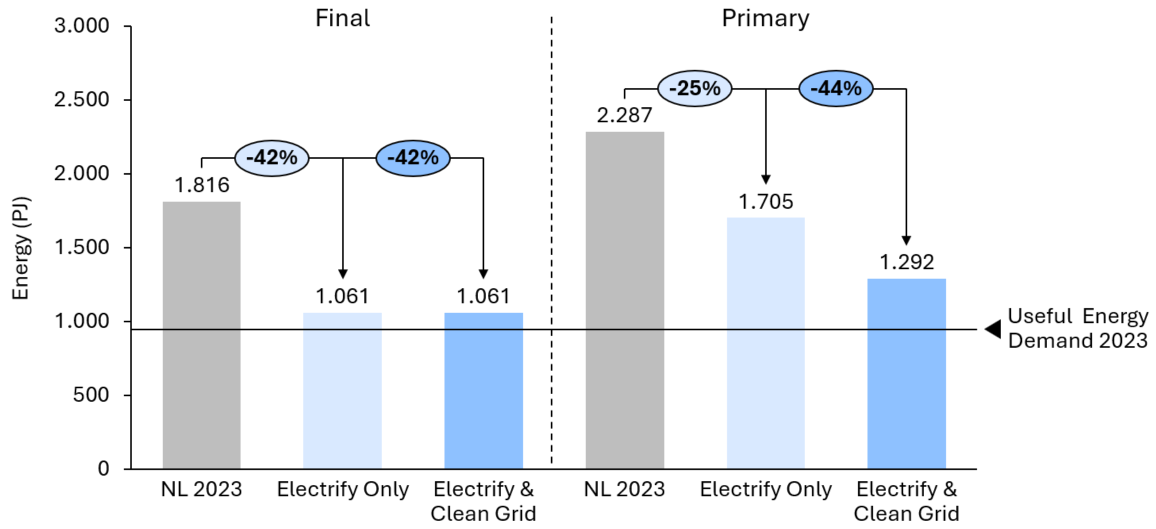


Figure 6: Cross-sectoral scenarios: Electrify Only and Electrify & Clean Grid vs. Baseline (NL 2023).

In terms of final energy, both the Electrify Only and the Electrify & Clean Grid scenarios demonstrate an identical 42 percent reduction, decreasing the demand from the baseline of 1,816 PJ to 1,061 PJ. This identical outcome is expected, as the end-use technology deployment remains exactly the same in both scenarios.

However, a significant divergence becomes apparent when analyzing the primary energy requirements. While the Electrify Only scenario, operating on the baseline electricity mix, achieves a 25 percent reduction in primary energy (dropping from 2,287 PJ to 1,705 PJ), coupling electrification with a decarbonized power supply yields much deeper systemic savings. The Electrify & Clean Grid scenario substantially reduces the primary energy demand by 44 percent, lowering it to 1,292 PJ. Compared to the Electrify Only scenario, this represents an additional primary energy saving of 413 PJ directly attributable to the decarbonized electricity mix.

4. Discussion

4.1. Useful Energy Balance

Our analysis of the Dutch energy balance demonstrates how the lens of useful energy does indeed have an important role to play in reframing energy policy discourses. Analyses which take final energy to be the measure of energy demand understate the role that electrons currently play in providing energy services, given that they make up 34% of useful energy but only 23.5% of final energy.

Through our analysis, it becomes evident that electricity operates at a substantially higher efficiency than molecules. For molecules, a final energy input of 1,223 PJ results in 613 PJ of useful energy, corresponding to an end-use efficiency of approximately 50%. For electricity, a final energy input of 376 PJ yields 326 PJ of useful energy, equating to a conversion efficiency of roughly 87%. The difference between the shares of final and useful energy is explained by this difference in end-use conversion efficiencies.

4.2. End-use electrification scenarios

The industry, built-environment and road-transport scenarios all express a single mechanism: replacing a combustion device with a more efficient electric one delivers the same useful energy from less final energy. The relative saving is largest where the displaced technology was least efficient, which is why road transport (internal-combustion efficiency near 20%) shows deeper reductions than heating. The overall effect on the final energy budget is illustrated by the “Electrify Only” scenario in Figure 6, with final energy demand reducing by 42% as compared to the NL 2023 baseline.

In each individual electrification scenario, and in the “Electrify Only” joint scenario, primary energy also reduces, but to a lesser extent than final energy. This is because (a) more primary energy is used for electricity generation, as an immediate corollary of substituting for end-use conversion devices that run on electricity, (b) electricity generation and transport introduces greater losses from primary energy, as compared to the transport of oil or natural gas, and (c) the size of these losses is less than the efficiency gains at the end-use stage.

Although the electrification scenarios improve the overall efficiency of the energy chain (i.e., the conversion efficiency from primary energy to useful energy) and can therefore achieve energy savings by delivering more useful services with less primary energy input, improving end-use energy efficiency alone is insufficient to achieve deep decarbonization. Further optimization of the electricity generation mix, and increased deployment of low-carbon electricity sources are required to reduce conversion losses.

4.3. Contrast Scenarios: NG CCS and District Heating

The NG CCS and District Heating scenarios provide two different contrasting cases to the electrification scenarios.

The NG CCS scenario is the only pathway in which both final (+22%) and primary energy (+9%) rise. Retaining an inefficient combustion process and adding the CCS energy penalty produces no end-use efficiency gain to offset the additional input. Its significance becomes clearest in comparison with the Electrify & H_2 scenario, since both can be read as routes to decarbonising the same industrial heat demand. Where Electrify & H_2 cuts final energy by 63% and primary energy by 44%, NG CCS moves in the opposite direction, requiring substantially more of both to deliver the identical useful heat. Meeting the heat demand while retaining natural gas is therefore far more energy-intensive than electrifying it, even when the fossil route is paired with carbon capture.

The District Heating scenario considers a maximally feasible rollout of district heating systems. Similarly to the electrification scenarios, this leads to a decrease in final energy demand, because district heating set-ups efficiently convert final energy to useful energy. In this case, it is because district heating systems deliver energy to consumers as hot water already, reducing end-use conversion losses compared to gas boilers. Compared to the electrification scenarios, the reduction in final energy is modest. Moreover, at the level of primary energy, it is offset by the inefficiencies and losses in the heating grid. These losses outweigh the increase in efficiency at the end-use level, meaning that there is a net increase in primary energy. However, a significant portion of primary energy is now provided by renewable and sustainable geothermal sources.

4.4. The Electricity Mix

The cross-sectoral scenarios show that the primary energy savings of a highly electrified system rest on two roughly equal contributions: one from the electrification of end uses itself, and a second, almost equally large, from transitioning the electricity generation mix towards renewables.

The two scenarios deploy identical (electrified) end-use technologies, and thus differ only in the electricity generation mix which isolates this second effect: final energy falls by the same 42% in both, since it depends on what consumers use rather than how electricity is produced, but primary energy diverges sharply, from a 25% reduction on the 2023 mix to 44% with the decarbonised "Eigen Vermogen 2050" mix, a further 413 PJ from cleaner generation alone.

The mechanism behind this divergence is the primary energy factor of electricity, which captures how much primary energy is drawn to deliver one unit of electricity. It falls from 1.84 on the 2023 mix to 1.26 on the decarbonised mix. This drop arises because, under the physical-energy-content convention, wind and solar are assigned a primary-to-final efficiency of 100%, since they require no fuel input, whereas the fossil generation they replace burns far more primary energy than it delivers as electricity. End use electrification and grid decarbonisation are comparable in magnitude and complementary: the first lowers the energy needed to deliver each service, the second the primary energy needed to supply it, and each alone captures only part of the saving. The full reduction is reached only when both advance together. Because these deeper savings come from displacing fossil generation, they point toward lower emissions as well, although the model tracks energy rather than emissions directly.

4.5. Limitations and future research

Our energy balance accounting contains some inherent simplifications. We only consider conversion device efficiency in the calculation of useful energy, and do not include passive losses. These passive losses, occurring from factors like cars drag coefficient or environmental factors such as wind speed and temperature, meaningly impact real world energy consumption (Cullen & Allwood, 2010). It was imperative however to balance accuracy with feasibility and thus passive losses were excluded.

Additionally, primary energy efficiencies for solar and wind are conventionally set at 100% as is standard in energy statistics, despite this not reflecting the true nature of renewable energy systems.

Assumptions were made regarding efficiencies in the transport sector. Multiple literature sources were compiled to find estimates for the tank to wheel (TTW) efficiencies, none of which were specific to the Dutch context. Newer cars are more efficient, and so further research could extend the analysis by deriving estimates based on the makeup of the current fleet of Dutch trains and cars.

There were several sectors which we excluded from our calculations. First, feedstock (e.g. oil & natural gas) used to manufacture materials was not included as by our definition of useful energy, the end use is not a form of useful energy but useful material which was outside the scope of our study. We also decided to exclude the marine and aviation transport subsectors as the international nature of their operations means the final energy they consumer are bunker fuels, fuels stored in tanks within the Netherlands, but used outside of the country. We therefore excluded these sub sectors for simplicity and consistency across our calculations. Future research should further consider the implications of including or excluding bunker fuels from useful energy balances.

The JRC-IDEES sub-models employed in this study are EU-harmonized, with end-use shares and conversion efficiencies for the residential and tertiary sectors derived from a generic European model rather than from Dutch-specific measurements. Only biomass calibration reflects Dutch conditions, somewhat limiting the geographic specificity of the model. Additionally, the model represents the energy balance from 2023 and therefore does not accurately reflect the present situation, which may limit its applicability to current policy decisions and real-world energy system assessments.

District heating presents a particular aggregation challenge within our modelling framework. We treat district heating as a distinct energy carrier with a single primary-to-final conversion factor, when in reality it comprises multiple primary energy sources each with their own conversion factors (geothermal, natural gas, and waste heat, etc.) Future studies should enhance the model by incorporating values for waste heat generated by industry and power plants as potential district heating sources, and by developing a disaggregated district heating module allow for more detailed scenario analysis.

The scenarios in this study compare technologies by how much final and primary energy they require to deliver a fixed amount of useful energy. This makes efficiency directly visible, but it also means that the most energy-efficient option is not necessarily the most climate-friendly one. Final and primary energy measure how much energy a service consumes, not how clean that energy is, so optimising for them alone can favour technologies that score well on energy while overlooking their emissions. The district-heating scenario illustrates this: primary energy rises slightly, not because renewable supply is inefficient, but because the heat network carries distribution losses that a domestic boiler does not. Yet a large share of that primary energy is now renewable geothermal rather than fossil gas, so a technology that looks worse in energy terms can in fact deliver a cleaner system. Optimising for final and primary energy alone is therefore an incomplete basis for technology choice unless environmental performance is considered alongside it.

Finally, it is important to note that all scenarios presented in this study are strong simplifications and should be regarded as exploratory rather than realistic projections. They serve to illustrate directional relationships and trade-offs within the energy system, but should not be interpreted as definitive forecasts of future energy transition pathways.

5. Conclusion

This study developed a transparent, all-sector useful energy balance for the Netherlands to provide a more complete understanding of how energy carriers contribute to delivering energy services. By extending existing energy statistics beyond final energy and incorporating useful energy, this research demonstrates that the current energy system looks different depending on the perspective applied. Although molecules account for a larger share of final energy consumption, their contribution decreases when conversion losses are considered. In the 2023 Dutch energy system, electricity provides approximately 1/3 of useful energy, despite representing only around 1/4 of final energy consumption. At the level of primary energy and useful energy, the relative contribution of electrons and molecules remains approximately comparable, with electricity accounting for roughly 1/3 and molecules for 2/3.

The scenario analysis further shows that electrification can significantly improve the efficiency of the Dutch energy system when the same level of useful energy demand is maintained. Across industry, the built environment, and transport, replacing combustion-based technologies with electric alternatives reduces final energy demand and lowers primary energy requirements. The cross-sectoral scenarios demonstrate that end-use electrification alone can reduce primary energy demand by 25% compared with the current system. Furthermore, the optimization of electricity supply mix also contributes on saving primary energy. Combining electrification with a decarbonized electricity system approximately doubles the achievable primary energy reduction, highlighting that demand-side transformation and clean electricity generation are complementary rather than competing strategies.

The useful energy perspective therefore provides an important addition to traditional energy statistics and can support more informed discussions about future energy pathways. Rather than focusing only on the quantity of energy carriers supplied, energy planning can be reframed around the services that the energy system must deliver and the efficiency with which these services are provided. This approach reveals the existing role of electricity in the energy system and demonstrates the potential efficiency gains associated with electrification.

Nevertheless, the results should be interpreted within the limitations of the modelling approach. The useful energy balance relies on assumptions regarding technology efficiencies, sectoral allocation, and future technology deployment. And the scenarios are not predictions of the future, but illustrative comparisons of different pathways under constant useful energy demand. Future research could further improve the balance by incorporating more Dutch-specific efficiency data, detailed district heating modelling, and environmental indicators alongside energy efficiency.

Overall, this research demonstrates that a useful energy perspective can provide a valuable framework for analysing the Dutch energy transition. The transition towards a more efficient and low-carbon energy system requires both the electrification of end uses and the continued transformation of the electricity supply system.

References

Aijjou, A., Bahatti, L., & Raihani, A. (2020). Analysis of container ship energy systems. *International Journal of Energy Production and Management, 5*(2), 142–156. https://doi.org/10.2495/EQ-V5-N2-142-156

Akay ME, Ustaoglu A. (2022). Energetic, exergetic, and environmental evaluation of railway transportation by diesel and electric locomotives. *Environmental Progress & Sustainable Energy 2022;41(3):e13804*. doi:10.1002/ep.13804

Cairney, P. (2016). *The Politics of Evidence-Based Policy Making*. Springer.

Cleveland, C., & Morris, K. (2015), *Dictionary of energy* (2nd ed., pp. 217–246). Elsevier. https://doi.org/10.1016/B978-0-08-096811-7.50006-8

Cullen, J., Allwood, J. (2010). The efficient use of energy: Tracing the global flow of energy from fuel to service. *Energy Policy Volume 38*, Issue 1, 75-81. https://doi.org/10.1016/j.enpol.2009.08.054

Cunanan, C., Tran, M.-K., Lee, Y., Kwok, S., Leung, V., & Fowler, M. (2021). A Review of Heavy-Duty Vehicle Powertrain Technologies: Diesel Engine Vehicles, Battery Electric Vehicles, and Hydrogen Fuel Cell Electric Vehicles. *Clean Technologies, 3*(2), 474-489. https://doi.org/10.3390/cleantechnol3020028

Daioglou, V., Faaij, A. P. C., Saygin, D., Patel, M. K., Wicke, B., & Vuuren, D. P. van. (2014). Energy demand and emissions of the non-energy sector. *Energy & Environmental Science*, *7*(2), 482–498. https://doi.org/10.1039/C3EE42667J

De Stercke, S. (2014). *Dynamics of energy systems: A useful perspective* (IIASA Interim Report No. IR-14-013). International Institute for Applied Systems Analysis. https://www.iiasa.ac.at/

Durack, M. (2016). Making sense of two — wheeler fuel efficiencies. *Auto Tech Rev* **5**, 20–25. https://doi.org/10.1365/s40112-016-1215-7

Dutch government (n.D.). Klimaatwet, https://wetten.overheid.nl/jci1.3:c:BWBR0042394&z=2026-01-01&g=2026-01-01 ; Retrieved 2026

EMBER. (2026). *Reframing energy for the age of electricity.* https://ember-energy.org/latest-insights/reframing-energy-for-the-age-of-electricity/

Fell, M. J. (2017). Energy services: A conceptual review. *Energy Research & Social Science*, *27*, 129–140. https://doi.org/10.1016/j.erss.2017.02.010

Helmers, E., & Marx, P. (2012). Electric cars: Technical characteristics and environmental impacts. *Environmental Sciences Europe, 24*(1), 14. https://doi.org/10.1186/2190-4715-24-14

IEA. (2023, July 11). *Electrification.* IEA. https://www.iea.org/energy-system/transport/electrification

IEA, (2024). World Energy Balances, IEA.https://www.iea.org/data-and-statistics/data-product/world-energy-balances.

Marina, A., Spoelstra, S., Zondag, H. A., & Wemmers, A. K. (2021). An estimation of the European industrial heat pump market potential. Renewable and Sustainable Energy Reviews, 139, 110545. https://doi.org/10.1016/j.rser.2020.110545

Netbeheer Nederland. (2025). Netbeheer Nederland Scenario's Editie 2025. https://www.netbeheernederland.nl/publicatie/netbeheer-nederland-scenarios-editie-2025

Paoli, L., Lupton, R. C., & Cullen, J. M. (2018). Useful energy balance for the UK: An uncertainty analysis. *Applied Energy, 228*, 176–188. https://doi.org/10.1016/j.apenergy.2018.06.063

van Polen, S., Wetzels, W., van Beijnum, B., Poorthuis., W & Blok, J. (2025). *Actualisatie Startanalyse Aardgasvrije Buurten 2025: Kernrapport met de nationale resultaten op hoofdlijnen [Machine Translated].*

Rademaker, K., & Marsidi, M. (2019). *Decarbonisation options for the Dutch paper and board industry.*

Ritchie, H. (2022). *Primary, secondary, final, and useful energy: Why are there different ways of measuring energy?* Our World in Data.https://archive.ourworldindata.org/20251125-173858/energy-definitions.html

Rózsai, M., Jaxa-rozen, M., Salvucci, R., Sikora, P., GEA, B. J., & Neuwahl, F. (2026). *JRC-IDEES-2023: The Integrated Database of the European Energy System*.

Rodriguez, M., Pansera, M., & Lorenzo, P. C. (2020). Do indicators have politics? A review of the use of energy and carbon intensity indicators in public debates. Journal of Cleaner Production, 243, 118602. https://doi.org/10.1016/j.jclepro.2019.118602

Scheepers, M., Palacios, S. G., Jegu, E., Nogueira, L. P., Rutten, L., van Stralen, J., Smekens, K., West, K., & van der Zwaan, B. (2022). Towards a climate-neutral energy system in the Netherlands. Renewable and Sustainable Energy Reviews, 158, 112097. https://doi.org/10.1016/j.rser.2022.112097

Statistiek, C. B. voor de. (2026, May 11). Centraal Bureau voor de Statistiek [Webpagina]. Centraal Bureau voor de Statistiek. https://www.cbs.nl/nl-nl

Tat, M. E., & Hosgor, O. (2023). Sustainability evaluation of a heavy-duty diesel engine used in railways. *Energy, 270*, 126853. https://doi.org/10.1016/j.energy.2023.126853

Teng, M., van Dam, K., & Hesselink F. (2025). *Warmten(i)et vastgelopen: Analyse naar de netimpact van geothermie en alternatieven voor de gebouwde omgeving [machine translated].*

Thermona (2010). Operation and Maintenance Manual for Electric Boilers.

Wu, Y., & Jang, C. (2019). Combustion Analysis of Homogeneous Charge Compression Ignition in a Motorcycle Engine Using a Dual-Fuel with Exhaust Gas Recirculation. *Energies.*

Zheng, Y., Gao, L., He, S., & Jin, H. (2023). Reduction potential of the energy penalty for CO2 capture in CCS. *Frontiers in Energy*, *17*(3), 390–399. https://doi.org/10.1007/s11708-023-0864-x

Appendix I

Table 6: Efficiencies of Different Coversion Devices (Helmers & Marx, 2012; Cunanan et al., 2021; Aijjou, Bahatti, & Raihani, 2020).

Sector	Subsector	Conversion Devices		Efficiency (%)	References
Transport	Road	Gasoline engine	Two-wheelers	10.5	Durack 2016
			Passenger car	19.5	Helmers & Marx, 2012
			Heavy vehicle	19.5	Use passenger car data as an approximation assumption.
		Diesel oil engine	Passenger car	25.5	Helmers & Marx, 2012
			Heavy vehicle	23.0	Cunanan et al., 2021
		LPG engine	Passenger car	16.0	Helmers & Marx, 2012
			Heavy vehicle	16.0	Use passenger car data as an approximation assumption.
		Natural gas engine	Passenger car	23.0	Helmers & Marx, 2012
			Heavy vehicle	23.0	Use passenger car data as an approximation assumption.
		Battery electric vehicles	Passenger car	81.0	Helmers & Marx, 2012
			Heavy vehicle	68.0	Cunanan et al., 2021
	Rail	Diesel oil engine	/	29.1	Akay & Ustaoglu, 2022
		Battery electric vehicles	/	43.4	Akay & Ustaoglu, 2022
	Navigation	Diesel oil engine	/	35	Aijjou, Bahatti, & Raihani, 2020

Appendix II

Table 7: Useful Energy Efficiency Calculation Sheet for the Transportation Sector.

Sector	Subsector	Fuel	Share Conversion Devices (%)					
			Gasoline engine	Diesel oil engine	LPG engine	Natural gas engine	Battery electric vehicles	Total
Transport	Road	Oil Products	Two-wheelers: 1.5% Passenger car: 47.2% Heavy vehicle: 0.3%	Passenger car: 11.5% Heavy vehicle: 38.1%	Passenger car: 1.1% Heavy vehicle: 0.3%			100%
		Natural gas				Passenger car: 94.8% Heavy vehicle: 5.2%		100%
		Biofuels and waste	Two-wheelers: 1.5% Passenger car: 45.5% Heavy vehicle: 0.3%	Passenger car: 12.2% Heavy vehicle: 40.4%		Passenger car: 0.1% Heavy vehicle: 0.01%		100%
		Electricity					Passenger car: 95.4% Heavy vehicle: 4.6%	100%
	Rail	Oil Products		100%				100%
		Biofuels and waste		100%				100%
		Electricity					100%	100%
	Domestic navigation	Oil products		100%				100%

Sector	Subsector	Fuel	TTW Efficiency (%)					
			Gasoline engine	**Diesel oil engine**	**LPG engine**	**Natural gas engine**	**Battery electric vehicles**	**Weighted Efficiency**
Transport	Road	Oil Products	Two-wheelers: 10.5% Passenger car: 19.5% Heavy vehicle: 19.5%	Passenger car: 25.5% Heavy vehicle: 23.0%	Passenger car: 16.0% Heavy vehicle: 16.0%			**21.3%**
		Natural gas				Passenger car: 23.3% Heavy vehicle: 23.3%		**23.3%**
		Biofuels and waste	Two-wheelers: 10.5% Passenger car: 19.5% Heavy vehicle: 19.5%	Passenger car: 25.5% Heavy vehicle: 23.0%		Passenger car: 23.3% Heavy vehicle: 23.3%		**21.5%**
		Electricity					Passenger car: 81.0% Heavy vehicle: 68.0%	**80.4%**
	Rail	Oil Products		29.1%				**29.1%**
		Biofuels and waste		29.1%				**29.1%**
		Electricity					43.4%	**43.4%**
	Domestic navigation	Oil products		35%				**35.0%**

Appendix III

Table 8: Methodological summary per sector. Source, calibration and decomposition applied, with Dutch-specific corrections.)

Sector	Source for final energy	Source for end-use shares and efficiencies	Calibration/Decomposition	Dutch-specific corrections
Industry (11 subsectors)	JRC-IDEES subsector sheets (CHI_fec, FBT_fec, ISI_fec, NFM_fec, NMM_fec, PPA_fec, TRE_fec, MAE_fec, TEL_fec, WWP_fec, OIS_fec)	JRC-IDEES subsector sheets (process-level FEC and UED)	Per-subsector totals reconcile to the JRC EnergyBalance industry totals (487.2 PJ overall)	Manual reclassification of the JRC processes into seven temperature-based end-use buckets to reflect the Dutch industrial context
Residential (Households)	JRC EnergyBalance, FC_OTH_HH_E by fuel (Eurostat-consistent)	JRC-IDEES residential sub-model (RES_hh_fec and RES_hh_eff)	Eurostat-consistent by construction	Biomass figure raised from 17.1 PJ (JRC sub-model) to 34.7 PJ (Eurostat balance) to remove the JRC undercount
Tertiary — Services	JRC EnergyBalance, FC_OTH_CP_E by fuel (Eurostat-consistent)	JRC-IDEES tertiary sub-model (SER_hh_fec and SER_hh_eff)	Eurostat-consistent by construction	Biomass figure raised from 6.5 PJ to 19.2 PJ; non-renewable waste folded into the biomass-and-renewables category
Tertiary — Agriculture	JRC-IDEES AGR_fec	JRC-IDEES AGR_fec and AGR_ued	Matches the Eurostat balance exactly	No correction needed
Transport (Road, Rail, Aviation, Domestic navigation)	JRC-IDEES transport energy sheets (TrRoad_ene, TrRail_ene, TrAvia_ene, TrNavi_ene); leaf fuels only	Paoli-style device-level decomposition: activity shares from the JRC transport activity sheets; tank-to-wheel efficiencies from the literature (Helmers and Marx, 2012; Cunanan et al., 2021; Aijjou, Bahatti and Raihani, 2020; Tat and Hosgor, 2023; Wu and Jang, 2019)	Useful energy derived through Paoli-style decomposition (Paoli et al., 2018)	International aviation excluded; international maritime bunkers treated as a memo item; parent fuel categories ("Liquids", "Renewable energies and wastes") excluded to avoid double counting
Feedstock (Chemicals)	JRC-IDEES CHI_fec, feedstock block	Not applicable; efficiency assumed to be 100% (Daioglou et al., 2014)	Matches the Eurostat FC_IND_CPC_NE total exactly	No correction needed

Sector	Source for final energy	Source for end-use shares and efficiencies	Calibration/Decomposition	Dutch-specific corrections
Energy sector own use	JRC EnergyBalance, NRG_E sub-sheets (NRG_PR_E, NRG_EHG_E, NRG_OIL_NG_E, NRG_CO_E, NRG_BF_E, NRG_NI_E)	Not applicable; efficiency = 0 (overhead with no useful service)	Eurostat-consistent	Added as a separate sector to enable reconciliation of the model with Dutch Gross Inland Consumption
Distribution losses	JRC EnergyBalance, DL sheet	Not applicable; efficiency = 0	Eurostat-consistent	Added as a separate sector for GIC reconciliation

Appendix IV

Table 9: Industry Processes - Bucket Classification (editable).

Every JRC industrial process (level-2 row of each subsector's _fec sheet) with the bucket the model currently assigns it. The 'Bucket - current' column (grey) is the model's classification; the 'Bucket - new' column (yellow) is editable via the dropdown. Change any rows you would like to reclassify and we can re-apply the changes to the balance and scenario workbooks.

Subsector	JRC code	Process (level-2 label)	Buckets
Iron and steel	ISI	Lighting	Motors & lighting
Iron and steel	ISI	Air compressors	Motors & lighting
Iron and steel	ISI	Motor drives	Motors & lighting
Iron and steel	ISI	Fans and pumps	Motors & lighting
Iron and steel	ISI	Low-enthalpy heat	Low-temp heat
Iron and steel	ISI	Steel: Sinter/Pellet-making	Process heat (high)
Iron and steel	ISI	Steel: Blast /Basic oxygen furnace	Process heat (high)
Iron and steel	ISI	Steel: Furnaces, refining and rolling	Process heat (high)
Iron and steel	ISI	Steel: Product finishing	Process heat (high)
Iron and steel	ISI	Steel: Smelters	Process heat (high)
Iron and steel	ISI	Steel: Electric arc	Process heat (high)
Non-ferrous metals	NFM	Lighting	Motors & lighting
Non-ferrous metals	NFM	Air compressors	Motors & lighting
Non-ferrous metals	NFM	Motor drives	Motors & lighting
Non-ferrous metals	NFM	Fans and pumps	Motors & lighting
Non-ferrous metals	NFM	Low-enthalpy heat	Low-temp heat
Non-ferrous metals	NFM	Alumina production: High-enthalpy heat	Process heat (high)
Non-ferrous metals	NFM	Alumina production: Refining	Process heat (high)

Subsector	JRC code	Process (level-2 label)	Buckets
Non-ferrous metals	NFM	Aluminium electrolysis (smelting)	Process heat (high)
Non-ferrous metals	NFM	Aluminium processing (metallurgy e.g. cast house, reheating)	Process heat (high)
Non-ferrous metals	NFM	Aluminium finishing	Process heat (medium)
Non-ferrous metals	NFM	Secondary aluminium (incl. pre-treatment, remelting)	Process heat (high)
Non-ferrous metals	NFM	Other Metals: production	Process heat (high)
Non-ferrous metals	NFM	Metal processing (metallurgy e.g. cast house, reheating)	Process heat (high)
Non-ferrous metals	NFM	Metal finishing	Process heat (medium)
Chemicals	CHI	Lighting	Motors & lighting
Chemicals	CHI	Air compressors	Motors & lighting
Chemicals	CHI	Motor drives	Motors & lighting
Chemicals	CHI	Fans and pumps	Motors & lighting
Chemicals	CHI	Low-enthalpy heat	Low-temp heat
Chemicals	CHI	Chemicals: Feedstock (energy used as raw material)	Feedstock (non-energy)
Chemicals	CHI	Chemicals: Steam processing	Low-temp heat
Chemicals	CHI	Chemicals: Furnaces	Process heat (high)
Chemicals	CHI	Chemicals: Process cooling	Cooling
Chemicals	CHI	Chemicals: Generic electric process	Motors & lighting
Chemicals	CHI	Chemicals: High-enthalpy heat processing	Process heat (medium)
Non-metallic minerals	NMM	Lighting	Motors & lighting
Non-metallic minerals	NMM	Air compressors	Motors & lighting
Non-metallic minerals	NMM	Motor drives	Motors & lighting
Non-metallic minerals	NMM	Fans and pumps	Motors & lighting

Subsector	JRC code	Process (level-2 label)	Buckets
Non-metallic minerals	NMM	Low-enthalpy heat	Low-temp heat
Non-metallic minerals	NMM	Cement: Grinding, milling of raw material	Low-temp heat
Non-metallic minerals	NMM	Cement: Pre-heating and pre-calcination	Process heat (medium)
Non-metallic minerals	NMM	Cement: Clinker production (kilns)	Process heat (high)
Non-metallic minerals	NMM	Cement: Grinding, packaging and precasting	Motors & lighting
Non-metallic minerals	NMM	Ceramics: Mixing of raw material	Low-temp heat
Non-metallic minerals	NMM	Ceramics: Drying and sintering of raw material	Low-temp heat
Non-metallic minerals	NMM	Ceramics: Primary production process	Process heat (high)
Non-metallic minerals	NMM	Ceramics: Product finishing	Process heat (medium)
Non-metallic minerals	NMM	Glass: Melting tank	Process heat (high)
Non-metallic minerals	NMM	Glass: Forming	Process heat (high)
Non-metallic minerals	NMM	Glass: Annealing	Process heat (medium)
Non-metallic minerals	NMM	Glass: Finishing processes	Motors & lighting
Pulp, paper and printing	PPA	Lighting	Motors & lighting
Pulp, paper and printing	PPA	Air compressors	Motors & lighting
Pulp, paper and printing	PPA	Motor drives	Motors & lighting
Pulp, paper and printing	PPA	Fans and pumps	Motors & lighting
Pulp, paper and printing	PPA	Low-enthalpy heat	Low-temp heat
Pulp, paper and printing	PPA	Pulp: Wood preparation, grinding	Low-temp heat
Pulp, paper and printing	PPA	Pulp: Pulping	Low-temp heat
Pulp, paper and printing	PPA	Pulp: Cleaning	Low-temp heat
Pulp, paper and printing	PPA	Paper: Stock preparation - Thermal	Low-temp heat

Subsector	JRC code	Process (level-2 label)	Buckets
Pulp, paper and printing	PPA	Paper: Stock preparation - Mechanical	Motors & lighting
Pulp, paper and printing	PPA	Paper: Paper machine	Low-temp heat
Pulp, paper and printing	PPA	Paper: Product finishing	Low-temp heat
Pulp, paper and printing	PPA	Printing and publishing	Low-temp heat
Food, beverages and tobacco	FBT	Lighting	Motors & lighting
Food, beverages and tobacco	FBT	Air compressors	Motors & lighting
Food, beverages and tobacco	FBT	Motor drives	Motors & lighting
Food, beverages and tobacco	FBT	Fans and pumps	Motors & lighting
Food, beverages and tobacco	FBT	Low-enthalpy heat	Low-temp heat
Food, beverages and tobacco	FBT	Food: Oven (direct heat)	Low-temp heat
Food, beverages and tobacco	FBT	Food: Specific process heat	Low-temp heat
Food, beverages and tobacco	FBT	Food: Steam processing	Low-temp heat
Food, beverages and tobacco	FBT	Food: Drying	Low-temp heat
Food, beverages and tobacco	FBT	Food: Process cooling and refrigeration	Cooling
Food, beverages and tobacco	FBT	Food: Electric machinery	Motors & lighting
Transport equipment	TRE	Lighting	Motors & lighting
Transport equipment	TRE	Air compressors	Motors & lighting
Transport equipment	TRE	Motor drives	Motors & lighting
Transport equipment	TRE	Fans and pumps	Motors & lighting
Transport equipment	TRE	Low-enthalpy heat	Low-temp heat
Transport equipment	TRE	Trans. Eq.: Foundries	Process heat (high)
Transport equipment	TRE	Trans. Eq.: Connection techniques	Motors & lighting

Subsector	JRC code	Process (level-2 label)	Buckets
Transport equipment	TRE	Trans. Eq.: Heat treatment	Process heat (high)
Transport equipment	TRE	Trans. Eq.: Steam processing	Process heat (medium)
Transport equipment	TRE	Trans. Eq.: General machinery	Motors & lighting
Transport equipment	TRE	Trans. Eq.: Product finishing	Motors & lighting
Machinery	MAE	Lighting	Motors & lighting
Machinery	MAE	Air compressors	Motors & lighting
Machinery	MAE	Motor drives	Motors & lighting
Machinery	MAE	Fans and pumps	Motors & lighting
Machinery	MAE	Low-enthalpy heat	Low-temp heat
Machinery	MAE	Mach. Eq.: Foundries	Process heat (high)
Machinery	MAE	Mach. Eq.: Connection techniques	Motors & lighting
Machinery	MAE	Mach. Eq.: Heat treatment	Process heat (high)
Machinery	MAE	Mach. Eq.: Steam processing	Process heat (medium)
Machinery	MAE	Mach. Eq.: General machinery	Motors & lighting
Machinery	MAE	Mach. Eq.: Product finishing	Motors & lighting
Textiles and leather	TEL	Lighting	Motors & lighting
Textiles and leather	TEL	Air compressors	Motors & lighting
Textiles and leather	TEL	Motor drives	Motors & lighting
Textiles and leather	TEL	Fans and pumps	Motors & lighting
Textiles and leather	TEL	Low-enthalpy heat	Low-temp heat
Textiles and leather	TEL	Textiles: Pretreatment with steam	Low-temp heat
Textiles and leather	TEL	Textiles: Wet processing with steam	Low-temp heat

Subsector	JRC code	Process (level-2 label)	Buckets
Textiles and leather	TEL	Textiles: Electric general machinery	Motors & lighting
Textiles and leather	TEL	Textiles: Drying	Low-temp heat
Textiles and leather	TEL	Textiles: Finishing Electric	Motors & lighting
Wood and wood products	WWP	Lighting	Motors & lighting
Wood and wood products	WWP	Air compressors	Motors & lighting
Wood and wood products	WWP	Motor drives	Motors & lighting
Wood and wood products	WWP	Fans and pumps	Motors & lighting
Wood and wood products	WWP	Low-enthalpy heat	Low-temp heat
Wood and wood products	WWP	Wood: Specific processes with steam	Low-temp heat
Wood and wood products	WWP	Wood: Electric mechanical processes	Motors & lighting
Wood and wood products	WWP	Wood: Drying	Low-temp heat
Wood and wood products	WWP	Wood: Finishing Electric	Motors & lighting
Other industrial sectors	OIS	Lighting	Motors & lighting
Other industrial sectors	OIS	Air compressors	Motors & lighting
Other industrial sectors	OIS	Motor drives	Motors & lighting
Other industrial sectors	OIS	Fans and pumps	Motors & lighting
Other industrial sectors	OIS	Low-enthalpy heat	Low-temp heat
Other industrial sectors	OIS	Other Industrial sectors: Steam processing	Low-temp heat
Other industrial sectors	OIS	Other Industrial sectors: Process heating	Process heat (medium)
Other industrial sectors	OIS	Other Industrial sectors: Drying	Low-temp heat
Other industrial sectors	OIS	Other Industrial sectors: Process Cooling	Cooling
Other industrial sectors	OIS	Other Industrial sectors: Diesel motors (incl. biofuels)	Motors & lighting

Subsector	JRC code	Process (level-2 label)	Buckets
Other industrial sectors	OIS	Other Industrial sectors: Electric machinery	Motors & lighting

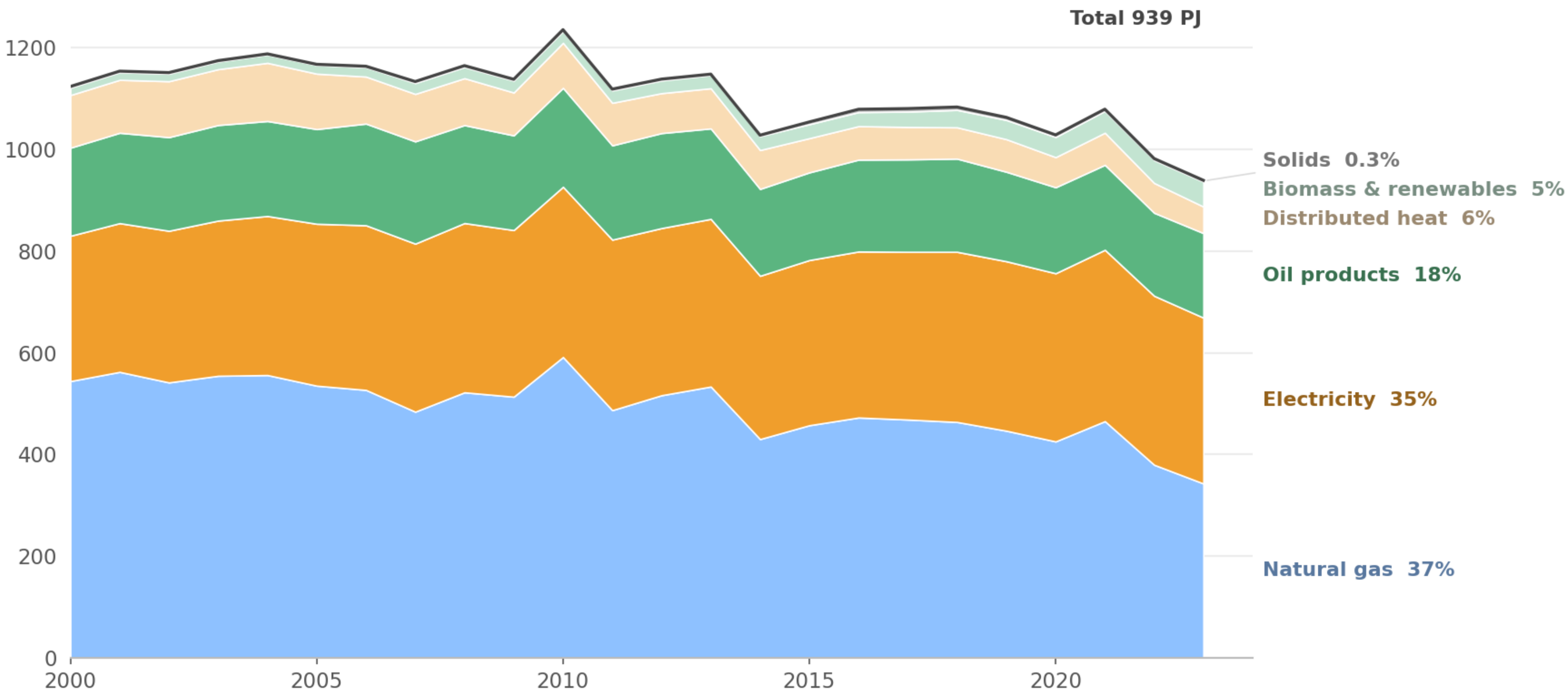
Appendix V

Table 10: Bucket Definitions.

Low-temp heat	Heat at low temperature, supplied as warm air or hot water.
Process heat (medium)	Process steam at roughly 150-450 °C, used in chemicals, food, paper, textiles. Drying processes are also placed here.
Process heat (high)	High-temperature heat in furnaces, kilns, smelters, ovens, melting tanks (above ~450 °C, often above 1000 °C).
Cooling	Process cooling and refrigeration.
Motors & lighting	Electric motors, lighting, fans and pumps, electric machinery, mechanical drives.
Feedstock (non-energy)	Fuels used as raw material; energy stays in the product. Currently only the chemical industry.

Appendix VI

Figure 7: Useful energy demand by carrier 2000-2023



Source: JRC-IDEES-2023 · NVDE useful-energy model (Useful = Final × Share × Efficiency). Energy use only; feedstock / non-energy use excluded.
Industry & agriculture efficiencies vary per year (JRC UED/FEC); other sectors hold 2023 end-use efficiencies. Excludes energy-sector own use & grid losses.