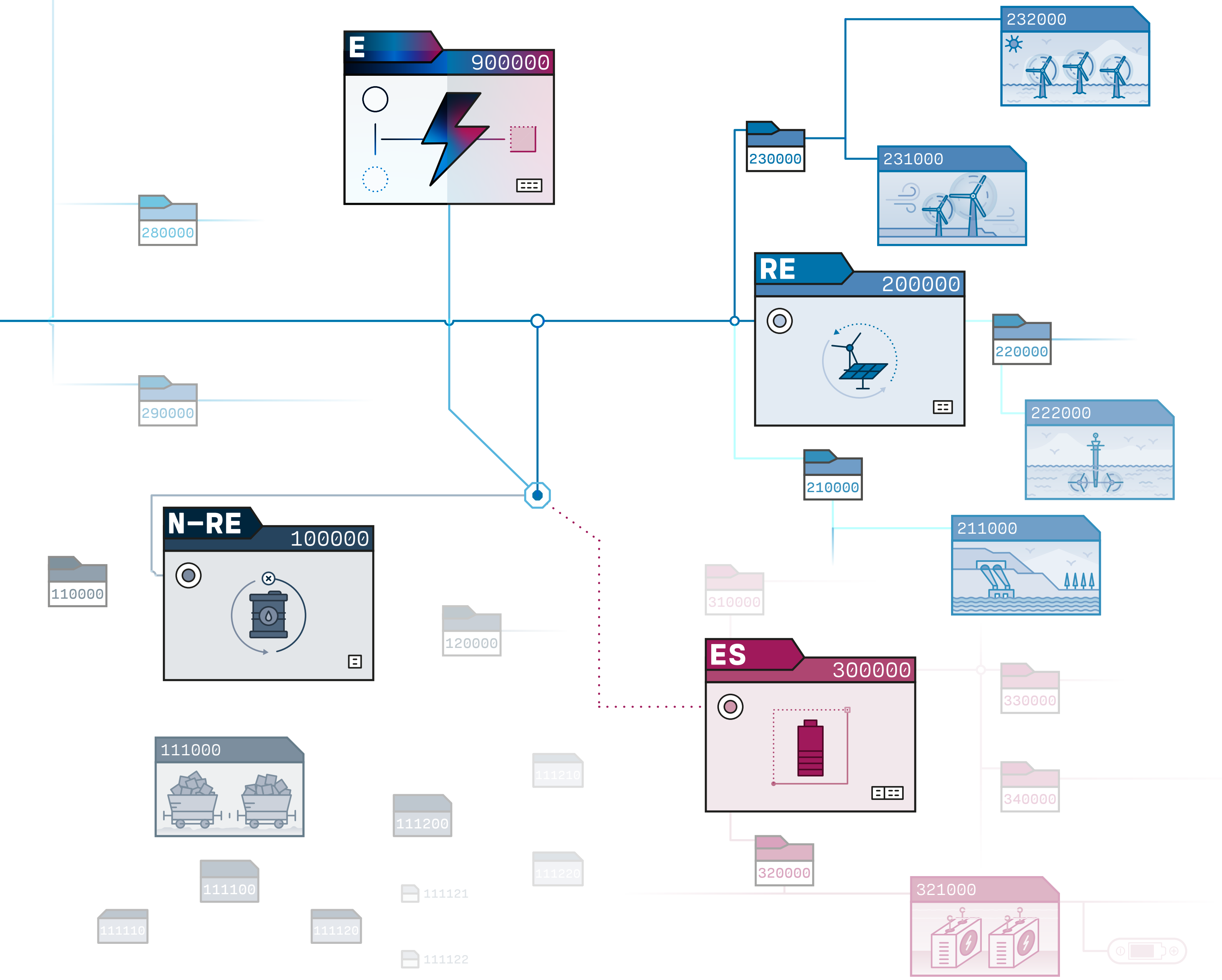
IRENA
International Renewable Energy Agency

ENERGY TAXONOMY

Classifications for the energy transition



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About IRENA

The International Renewable Energy Agency (IRENA) serves as the principal platform for international co-operation, a centre of excellence, a repository of policy, technology, resource and financial knowledge, and a driver of action on the ground to advance the transformation of the global energy system. An intergovernmental organisation established in 2011, IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity. **www.irena.org**

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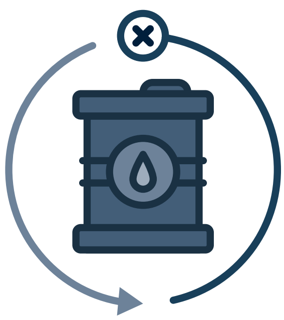

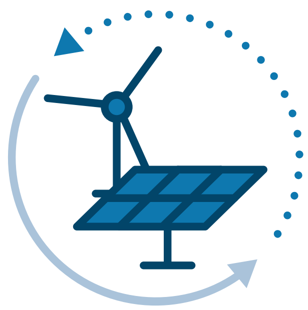

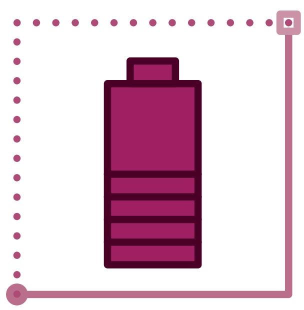

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WHY DO WE NEED AN ENERGY TAXONOMY?

Renewables are on the rise, yet they are misunderstood in energy statistics. In the past two decades, solar and wind energy have become integral components of political discourse, national policies and international agendas, energy markets and global supply chains. The ongoing renewable energy transition is undoubtedly led by the increasing renewable electricity generation capacity of wind and solar energy worldwide.

As the role of renewable energy grew in the power sector over the 2010s, many institutions, governments and businesses attempted to gather, categorise and make sense of renewable energy data for different purposes. Much of these data lacked comparison standards and specific methodologies to guarantee that the numbers were comparable across countries, energy sources and time. Often, the reports, databases and analyses developed by countries, regional and international organisations, and think tanks could not be easily compared to one another (and, sometimes, among themselves), therefore biasing potential analyses and crucial decision making.

IRENA has encountered these issues first hand while working with multiple countries and institutions. The Agency actively engages with Member State officials to understand their respective energy systems, collaborate on solutions and foster international collaboration. With a deeper understanding of national and regional institutional arrangements, and by overcoming challenges in the measurement and tracking of energy generation and consumption, as well as in collecting information about system maintenance, more meaningful insights can be drawn.

The current international energy product classifications are insufficient for decision makers. One of the fundamental issues with energy statistics is that the international consensus is not yet prepared to incorporate new and future energy systems. The International Recommendations for Energy Statistics (IRES),[1] published more than a decade ago,[2] do not go into detail about how to standardise energy information for renewable energy, which has taken a larger role in the global energy system since IRES was published. Although IRES introduced the Standard International Energy Product Classification, which has since been the backbone of international energy statistics, the classification of energy can become complicated when considering energy non-products, such as technologies, or certain product distinctions based on processing pathways. The energy systems of the future may necessitate an update to these recommendations to ensure energy data are standard across the world and easily comparable for policy makers.

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[1] IRES was prepared by the United Nations Statistics Division, the Oslo Group on Energy Statistics and the Intersecretariat Working Group on Energy Statistics in response to a request by the United Nations Statistical Commission, at its 37th session (7–10 March 2006), to review the United Nations manuals on energy statistics, develop energy statistics as part of official statistics, harmonise energy definitions and compilation methodologies and develop international standards in energy statistics. IRENA is part of the Intersecretariat Working Group on Energy Statistics and is undertaking a separate reclassification exercise for energy products as of 2024.

[2] The Intersecretariat Working Group on Energy Statistics published the first harmonised list of energy products in 2010; it was republished in IRES in 2011.

Updating international classifications of energy products would also help decentralised energy be better accounted for in energy balances, both for autoproducers and for small energy producers; this is one of the focuses of the ongoing revision of the Standard International Energy Product Classification (Russo, 2022). More importantly, amid the climate crisis of the 21st century, the priority should be to focus on emission-related energy classifications. The division of energy products and carriers between renewable and non-renewable, as incorporated in this taxonomy by IRENA, will help clarify the climate change impacts of the energy system.

Proposing an energy taxonomy focused on the renewable distinction. With this energy taxonomy, IRENA intends to emphasise the importance of categorising energy globally, starting with the question most relevant to the climate crisis: is the energy renewable or not? Increased demands for electrification of end uses (*e.g.* heating and transport) and for renewable electricity will only cause more confusion under the current SIEC. Renewable electricity is not currently classified, because electricity is just that: electricity. There is no physical difference between the electrons coming from renewable sources and those coming from fossil fuels or nuclear fuels – and the same is true of hydrogen and other synthetic fuels. In its published series of energy statistics, IRENA has expended much effort in classifying electricity according to its energy sources, because this information is important for policy makers focusing on climate change mitigation and adaptation. IRENA is now building on those classifications in the current taxonomy and using the same approach to classify synthetic fuels like hydrogen – proposing, for example, that hydrogen is placed under its source of energy, whether that is a specific fossil fuel, a biomass feedstock or an unspecified mix of fuels and energy carriers. Furthermore, there are now a myriad of hydrogen "colours",[3] which are difficult to remember at best and cause confusion and errors at worst. That is why IRENA suggests that hydrogen be named according to the fuel source used to produce it, stemming from a division between renewable and non-renewable sources.

This taxonomy also brings an additional division of energy: storage. As power sectors incorporate more renewable electricity, most grid-based systems will need a realistic approach to deal with variable electricity from solar and wind energy. One of these solutions is energy storage. In addition to the typical pumped hydropower storage, the IRENA taxonomy considers all the energy pathways to storage, including thermal, electric and chemical storage. Energy statisticians could use these classifications of storage to adequately link the different types of energy sources used to produce the stored energy so that energy storage can also be divided between renewable and non-renewable. This new way of classifying energy storage suggests that the international standard convention to account for pumped hydro, as explained in the Energy Statistics Compilers' Manual (UNSD, 2022), must also be revised to account for the increasing share of renewable electricity used to pump water.

[1] *Many organisations and government bodies have classified hydrogen using colour codes to specify its different energy sources and synthesis pathways. Hydrogen itself is always the same molecule, but determining from what and how it is produced is important to quantifying the greenhouse gas emissions related to its production. This taxonomy aims to clarify the sources and pathways of hydrogen production under the main division of "renewable" and "non-renewable" to address this information gap.*

A few caveats concerning this taxonomy. While this taxonomy proposes an initial distinction between renewables and non-renewables, it is difficult to attribute carbon emissions in their entirety to the classifications in this taxonomy; thus, this document is not intended to guide carbon accounting. For accurate carbon accounting, please refer to the established international guidelines from the United Nations Framework Convention on Climate Change, specifically within the Enhanced Transparency Framework. Furthermore, this taxonomy does not recommend methodologies for the overall process of working with energy statistics. Instead, please refer to IRES and the *Energy Statistics Compilers Manual*, published by the United Nations.

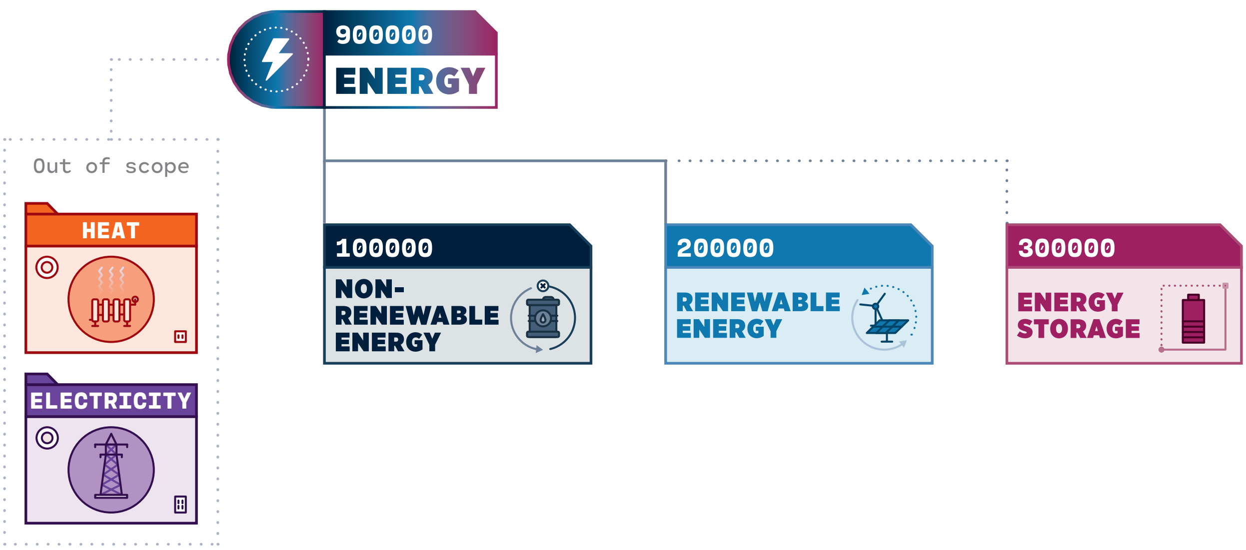
Next in IRENA's work. The proposed taxonomy is a work in progress, and IRENA will continue to refine the classifications in accordance with the overarching subdivisions of energy types and the international agreements on energy statistics from the Intersecretariat Working Group on Energy Statistics. This taxonomy started a dialogue within IRENA and eventually a discussion with international bodies about the standardisation of energy statistics. Feedback is welcome for this publication;[4] the objective is to incorporate these revised classifications into energy statistics at IRENA, including internal databases, methodologies to calculate shares of renewable energy, data visualisations, and design of data collection questionnaires shared with our Member States. IRENA encourages the international collaboration to continue on the harmonisation of energy classifications, carbon accounting, and matching with economic activity classifications used by national statistical offices all of which are crucial to the correct measurement of energy activities within different economic landscapes.

[4] *For further information or to provide feedback, please contact the IRENA Statistics team (statistics@irena.org).*

ENERGY TAXONOMY

The energy taxonomy proposed in this document groups all energy sources, products and uses under three main groups within "energy": non-renewable energy, renewable energy and energy storage. IRENA is categorising energy storage separately to acknowledge that its energy sources could be classified as a third group but that theoretically they could also be attributed to their primary energy source within renewable and non-renewable energy.

Figure 1 Main structure of the energy taxonomy for (total) energy and its components



Each of these three groups is considered level 1, the most aggregated group level. Within each group are multiple other groupings and subsections, going down to level 6. For ease of reference and grouping, IRENA classifies each energy product using a numerical code of six digits.

This taxonomy for energy products is based on the Standard International Energy Product Classification (SIEC), outlined in the International Recommendations for Energy Statistics (IRES) (UNSD, 2018), and matches the SIEC descriptions and energy methodology considerations as much as possible. In some cases, IRENA provides further classifications or modifications to existing SIEC products to comply with the overarching division of energy between renewable and non-renewable. For reference, IRENA uses the following icons in this report:

= CONSISTENT WITH SIEC → Refer to the SIEC description of these products, found in IRES (UNSD, 2018)

~ MODIFIED FROM SIEC

+ ADDITIONAL TO SIEC

PRIMARY → Energy products from natural energy flows, entering the energyqsystem for the first time (*e.g.* crude oil, natural gas, wind energy, wood fuel, anaerobic digestion biogas).

SECONDARY → Energy products from primary, or other secondary fuels or energy sources (*e.g.* oil products from crude oil, electricity from any source, hydrogen from electricity, biogas from pyrolysis of biomass).

PRIMARY AND SECONDARY → Occurring either as primary energy, or as products of primary or secondary energy sources.

⚠ Electricity and heat are not explicitly declared in this taxonomy. As they are energy carriers that can be produced from a wide range of energy products. IRENA treats them as their own energy flows, disconnected from the tree of classifications. IRENA's approach instead uses IRES to classify the energy sources used to produce the electricity and heat.

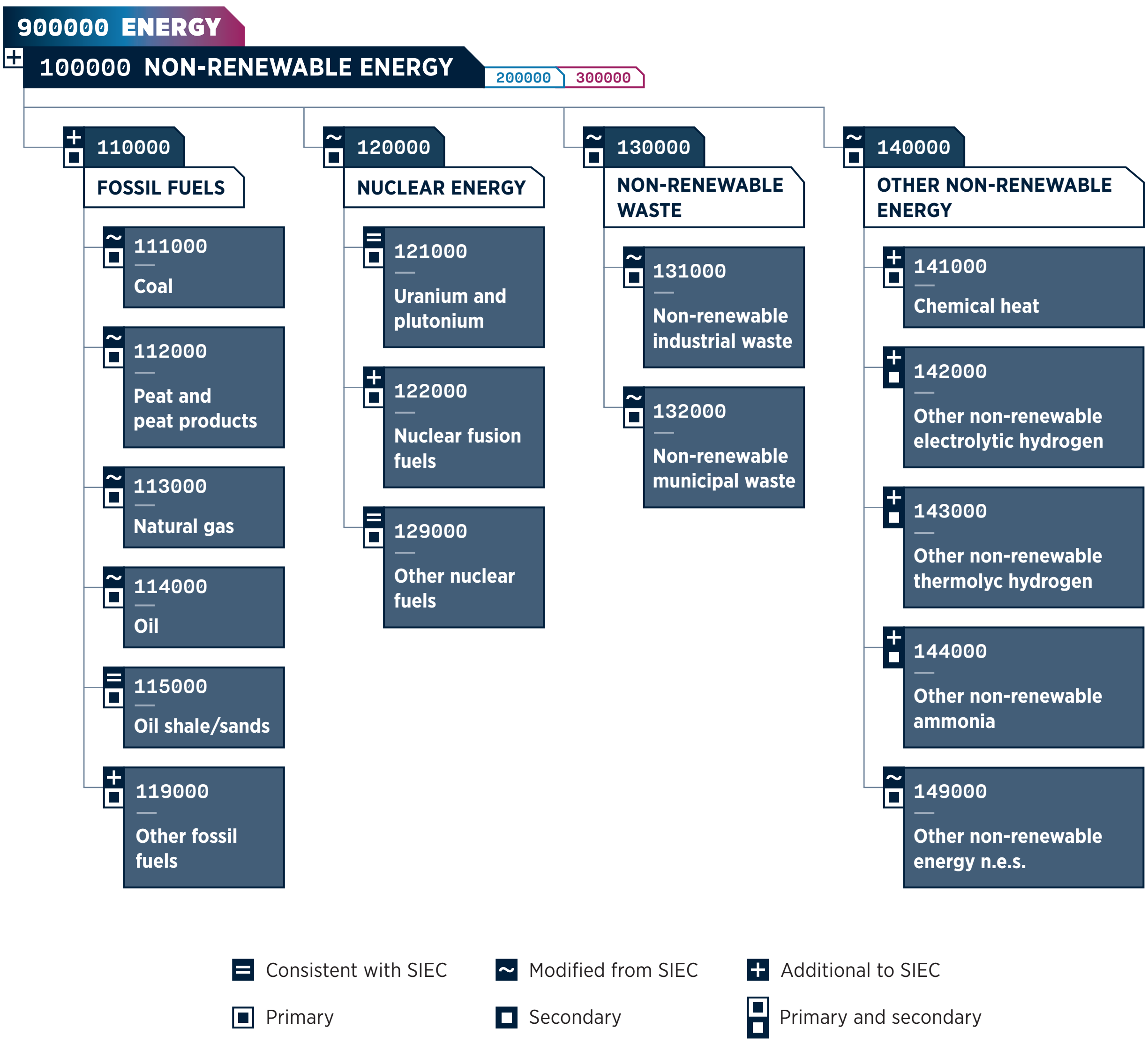
As of 2024, the United Nations Statistics Division is working on improving the current SIEC, and IRENA is actively engaged in this work. Among the improvements are clearer definitions of renewable and non-renewable energy. The distinction between renewables and non-renewables will remain as a secondary classification for energy products. This makes sense from a product perspective, as statistical offices categorise, count and account for energy products using energy, economic, or forestry statistics questionnaires. This taxonomy does not propose to replace this classification of products but rather to lay down an accounting framework for the sources of energy, divided by renewables and non-renewables. The text explains in more detail those categories proposed as new classifications or large modifications to the existing ones in SIEC.

⚠ The main classification groups proposed by IRENA are different than in the SIEC list outlined in IRES. Here, the main distinction starts with renewables and non-renewables, rather than these being secondary categories, as they are in IRES Annex A.

100000
NON-RENEWABLE ENERGY

Non-renewable energy is an aggregate category, comprising fossil fuels, nuclear energy, and other types of non-renewable energy, plus electricity and heat produced from these sources. Non-renewable energy is produced from fuels that are consumed faster than they can be replaced by natural means or whose use and consumption is unsustainable for the foreseeable future.

Figure 2 IRENA classification of non-renewable energy

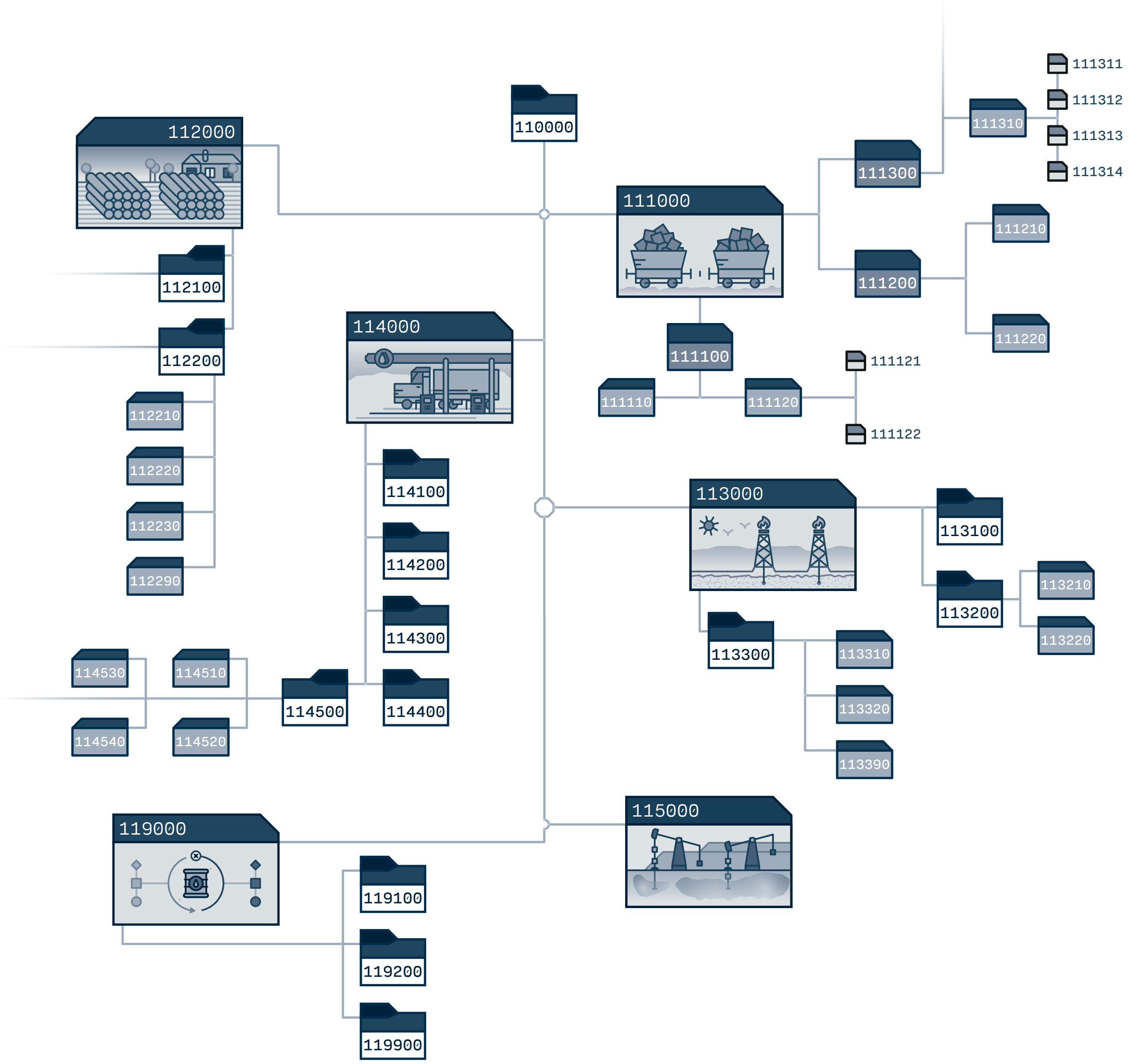


Note: n.e.s. = not elsewhere specified.

110000 FOSSIL FUELS

The fossil fuels category is an aggregate group for hydrocarbons formed from pressurised and heated organic material buried over millions of years. This category comprises coal, peat and peat products, natural gas, oil, oil shale/sands, and fossil fuels not elsewhere specified. Fossil fuels include both primary and secondary (processed) energy products and can be used for electricity and heat generation.

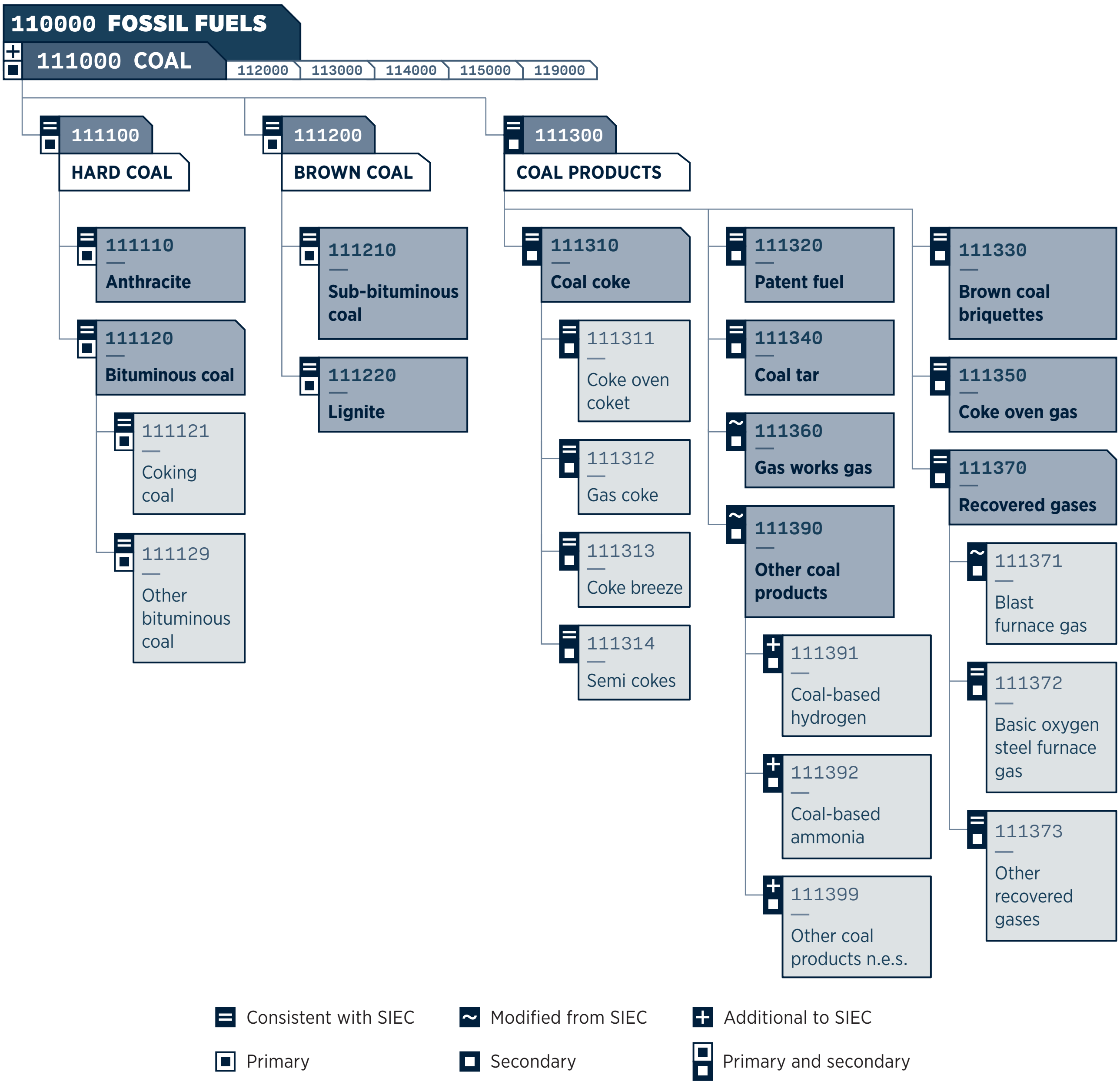
Fossil fuels are used for all types of energy production but are particularly important as a source of transport fuel. Fossil fuels may also be combined with renewable energy (*e.g.* co-firing fossil fuels with bioenergy in power stations, blending liquid biofuels with petrol or diesel, or mixing biomethane with natural gas in gas distribution networks). In such cases, the energy content of non-renewable and renewable energy in the mixed product should be reported separately under the appropriate headings.



111000 Coal

Coal is solid carbonised vegetal matter. This aggregate group comprises hard coal, brown coal and coal products.

Figure 3 SIEC classification of coal with IRENA coding and additional products



Note: n.e.s. = not elsewhere specified.

Coal is mostly used for heat or to generate electricity; globally, it is the most significant source of energy used to generate electricity. Relatively small amounts of coal are also used to produce chemicals (non-energy use), and these amounts are recorded in energy balances.

Table 1 Hard and brown coal classification based on vitrinite mean random reflectance (VMRR) and gross calorific value (GCV) on a moist, ash-free basis

VMRr (%) / GCV (MJ/kg)	< 20	20-24	≥ 24
≥ 2	Bituminous coal*	Bituminous coal*	Anthracite*
0.6-2	Bituminous coal*	Bituminous coal*	Bituminous coal*
< 0.6	Lignite**	Sub-bituminous coal**	Bituminous coal*

Notes: GCV = gross calorific value; MJ/kg = megajoule per kilogramme; VMRr = vitinite mean random reflectance; * hard coal; ** brown coal.

111100 Hard coal

111110 Anthracite

111120 Bituminous coal

- 111121 Coking coal
- 111129 Other bituminous coal

111200 Brown coal

111210 Sub-bituminous coal

111220 Lignite

111300 Coal products

111310 Coal coke

- 111311 Coke oven coke
- 111312 Gas coke
- 111313 Coke breeze
- 111314 Semi cokes

111320 Patent fuel

111330 Brown coal briquettes

111340 Coal tar

111350 Coke oven gas

111360 Gas works gas

Gas works gas is a group of gases obtained from the carbonisation or gasification of carbonaceous material of fossil origins in gas works (UNSD, 2018). The gases comprise (a) gases obtained from carbonisation or gasification of coals, cokes or non-renewable waste and (b) substitute natural gas (a methane-rich gas) made from synthesis gas.

⚠ Comparison to SIEC definition: IRENA has removed biomass as a source of gas works gas. IRENA considers that substitute natural gas should also be categorised under gas biofuels (263000) when it comes from biological origins and under non-bio renewable gas fuels (273000) when it comes from atmospheric carbon.

Synthesis gas is a mixture of mainly hydrogen and carbon monoxide obtained by cracking hydrocarbons with high-temperature steam. The hydrocarbons may come from fossil fuels, biofuels or wastes.

111370 Recovered gases

111371 Blast furnace gas

Blast furnace gas is the by-product gas of blast furnace operation, consisting mainly of nitrogen, carbon dioxide and carbon monoxide (UNSD, 2018). The gas is recovered as it leaves the furnace. Its calorific value arises mainly from the carbon monoxide produced by the partial combustion of coke and other carbon-bearing products in the blast furnace. It is used to heat blast air and as a fuel in the iron and steel industry. It may also be used by other nearby industrial plants.

⚠ When carbonised biomass (*e.g.* charcoal or animal meal) is used in blast furnaces, this part of the carbon supply should be considered renewable and classified under bioenergy. Specifically, under charcoal (261600).

111372 Basic oxygen steel furnace gas

111373 Other recovered gases

111390 Other coal products

Other coal products, including coal-based hydrogen and ammonia.

111391 Coal-based hydrogen

Coal-based hydrogen is hydrogen produced from coal or coal products as raw materials. Coal-based hydrogen is often produced by the gasification of coal and the refinement of syngas to separate hydrogen from carbon dioxide.

In gasification, coal is oxidised with steam and oxygen in a high-pressure and high-temperature reactor, producing carbon monoxide, hydrogen, carbon dioxide and steam (water). This mixture of gases can undergo a water-gas shift reaction to generate more hydrogen. This process releases around 30 kg of carbon dioxide per kilogramme of hydrogen (Younas *et al.*, 2022).

111392 Coal-based ammonia

Coal-based ammonia is ammonia produced from coal or coal products. It is regularly co-produced with coal-based hydrogen.

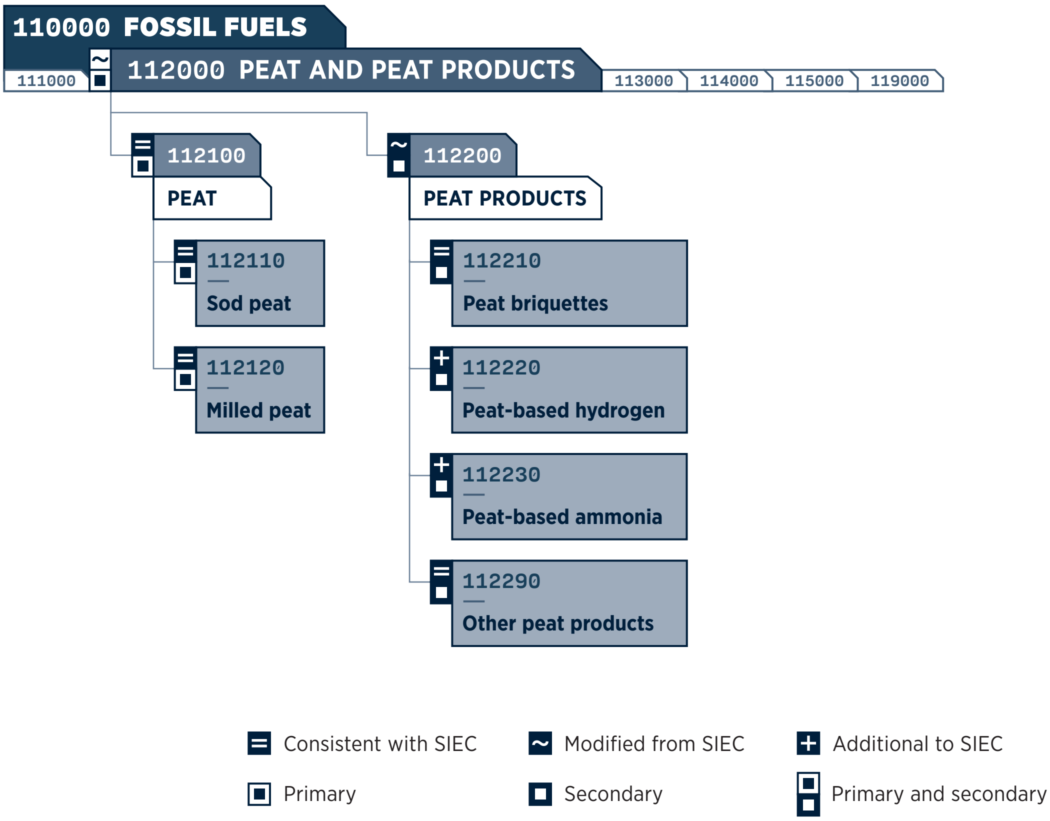
111399 Other coal products n.e.s.

Other coal products not elsewhere specified.

112000 Peat and peat products

Peat and peat products is an aggregate group made up of subcategories shown in Figure 4.

Figure 4 SIEC classification of peat and peat products with IRENA coding and additional products



112100 Peat

Peat is a "solid formed from the partial decomposition of dead vegetation under conditions of high humidity and limited air access (initial stage of coalification)" and any products derived from it (UNSD, 2018: 30). Peat is not strictly a fossil fuel, as it does regenerate slowly. However, in places where it is used as fuel, peat production generally exceeds the replacement rate, so it can be considered as a type of non-renewable energy.

Peat is an aggregate category for sod peat, milled peat and peat products.

112110 Sod peat

112120 Milled peat

112200 Peat products

Peat products is an aggregate category for energy products produced from peat: peat briquettes, peat-based hydrogen, peat-based ammonia and other peat products.

112210 Peat briquettes

112220 Peat-based hydrogen

Peat-based hydrogen is hydrogen produced from any synthesis pathway that uses peat or peat products as raw materials or fuel source.

112230 Peat-based ammonia

Peat-based ammonia refers to the ammonia produced from any synthesis pathway that uses peat or peat products as raw materials or fuel source. The most common pathway is through the pyrolysis or gasification of peat, which produces various gases including hydrogen, a raw material in the production of ammonia (Koljonen and Södervall, 1991).

112290 Other peat products

113000 Natural gas

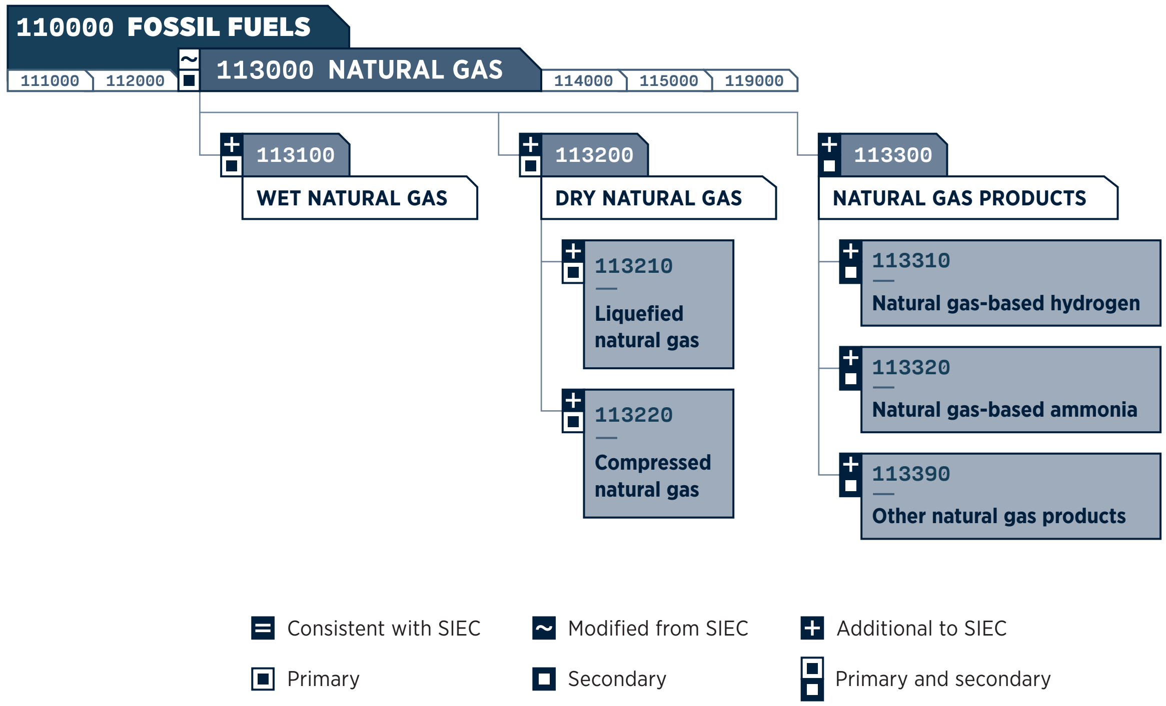
Natural gas is a mixture of hydrocarbon gases found in underground deposits. Natural gas is a product of the decomposition of organic matter trapped underground several thousand years ago. Methane is the largest component of natural gas, but natural gas also contains varying amounts of ethane, propane and heavier hydrocarbons, as well as smaller amounts of nitrogen, oxygen, carbon dioxide, sulphur compounds and water.

When distributed, natural gas may also contain biomethane from anaerobic digestion or the pyro-gasification of biomass. In such cases, the biomethane should be treated as a mix of non-renewable natural gas and renewable gas biofuels.

Natural gas is mostly used for heat or to generate electricity, but it may also be used as a transport fuel or to produce other materials (non-energy use). The natural gas used for purposes besides energy is currently included in energy statistics.

The natural gas aggregate group comprises wet natural gas, dry natural gas and natural gas products.

Figure 5 SIEC classification of natural gas with IRENA coding and additional products



113100 Wet natural gas

Wet natural gas refers to the gas recovered from natural gas or crude oil wells. It might contain natural gas liquids, liquefiable gases such as propane and butane, and other non-hydrocarbon gases, along with the methane.

113200 Dry natural gas

Dry natural gas is methane recovered from the ground that does not contain natural gas liquids, liquefiable gases or other non-hydrocarbon gases. The term also applies to the methane remaining after extracted natural gas has been processed to remove natural gas liquids and other non-hydrocarbons that make the gas unmarketable (EIA, n.d.).

113210 Liquefied natural gas

Liquefied natural gas is natural gas that is in liquid state at low temperature and low atmospheric pressure (EIA, n.d.).

113220 Compressed natural gas

Compressed natural gas is natural gas that has been compressed to more than 200 bar (EIA, n.d.). Compressed natural gas is often used as an alternative fuel for internal combustion engines.

⊞ 113300 Natural gas products

Natural gas products are secondary energy products synthesised from natural gas.

⊞ 113310 Natural gas-based hydrogen

Natural gas-based hydrogen is hydrogen produced from natural gas or natural gas products. Natural gas-based hydrogen is mainly produced by the steam methane reforming process (Rosen, 1991) or by methane pyrolysis (Guéret *et al.*, 1997).

In the steam methane reforming process, methane reacts with steam at high temperatures and pressure to produce hydrogen and carbon dioxide. This process is currently the most common method for producing hydrogen and accounts for around 80% of recent global hydrogen production (Younas *et al.*, 2022).

Methane pyrolysis involves heating methane at high temperatures without oxygen to produce hydrogen and solid carbon. Although this process is still in its experimental stages, it has the potential to produce hydrogen with significantly lower carbon emissions than steam methane reforming.

To reduce emissions, natural gas-based hydrogen can be paired with carbon capture and storage (CCS) technologies. The captured carbon dioxide is usually stored underground.

⊞ 113320 Natural gas-based ammonia

Natural gas-based ammonia is ammonia produced from natural gas or natural gas products. Often, this ammonia is a by-product of natural gas-based hydrogen.

⊞ 113390 Other natural gas products

Other natural gas products not elsewhere specified.

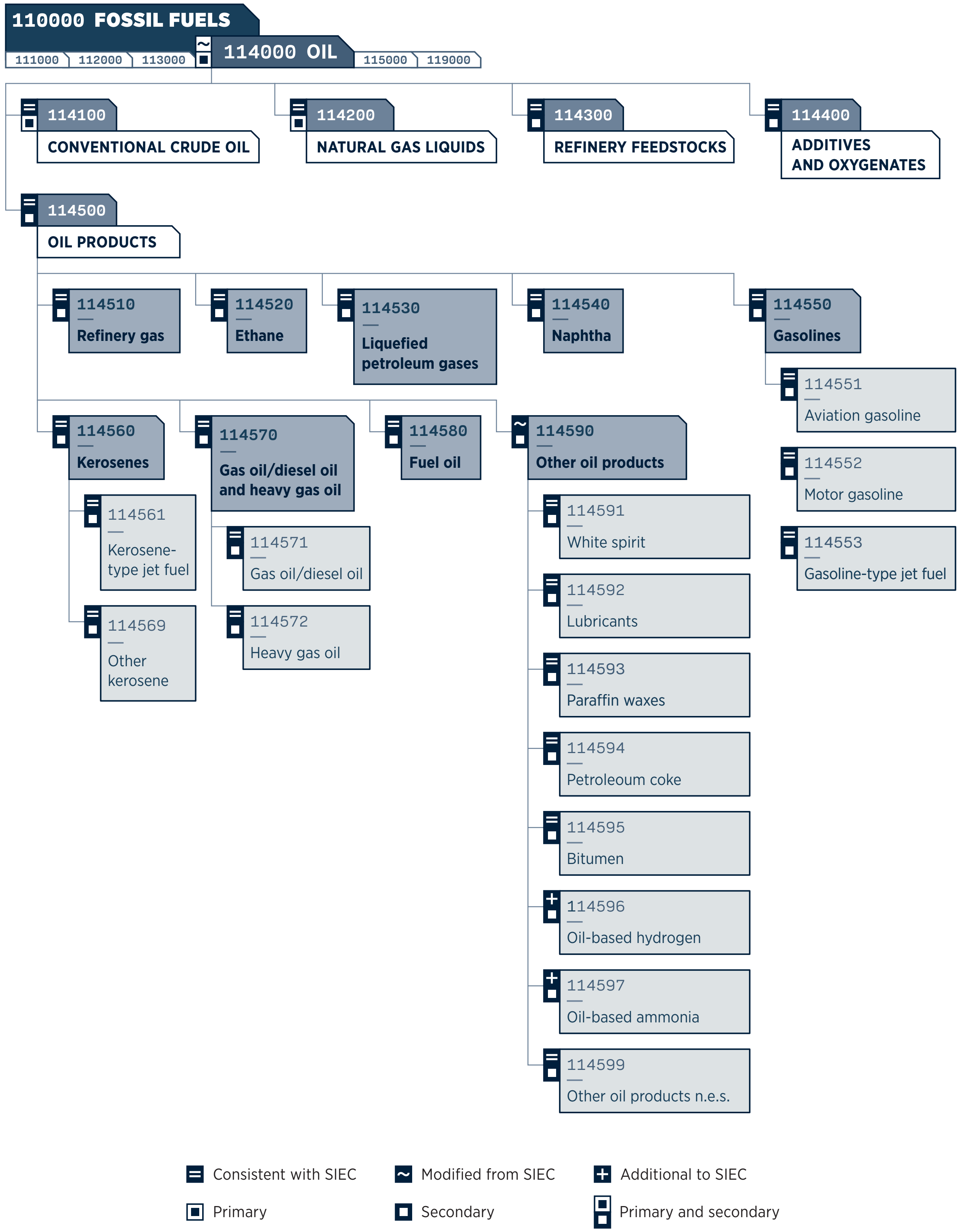
114000 Oil

Oil is a combustible liquid containing hydrocarbons and various other organic compounds.

Oil is an aggregate category comprising conventional crude oil, natural gas liquids, refinery feedstocks, additives and oxygenates, and oil products.

By volume, most oil is used as a transport fuel, but oil is also used for heating and electricity generation. A significant amount of oil is used as lubricant and to produce chemicals and plastics (non-energy use). The oil expended in these non-energy uses is recorded in energy statistics.

Figure 6 SIEC classification of oil with IRENA coding and additional products



Note: n.e.s. = not elsewhere specified.

- **114100 Conventional crude oil**
- **114200 Natural gas liquids**
- **114300 Refinery feedstocks**
- **114400 Additives and oxygenates**
- **114500 Oil products**

  - **114510 Refinery gas**
  - **114520 Ethane**
  - **114530 Liquefied petroleum gases**
  - **114540 Naphtha**
  - **114550 Gasolines**

    - 114551 Aviation gasoline
    - 114552 Motor gasoline
    - 114553 Gasoline-type jet fuel

  - **114560 Kerosenes**

    - 114561 Kerosene-type jet fuel
    - 114569 Other kerosene

  - **114570 Gas oil/diesel oil and heavy gas oil**

    - 114571 Gas oil/diesel oil
    - 114572 Heavy gas oil

  - **114580 Fuel oil**
  - **114590 Other oil products**

The other oil products category is an aggregate of oil products not classified elsewhere: white spirit, lubricants, paraffin waxes, petroleum coke, bitumen, oil-based hydrogen, oil-based ammonia and other oil products not elsewhere specified.

⚠ SIEC classifies hydrogen and ammonia under Other hydrocarbons. IRENA has instead added categories for hydrogen and ammonia under each fossil fuel used to synthesise them.

    - 114591 White spirit
    - 114592 Lubricants
    - 114593 Paraffin waxes
    - 114594 Petroleum coke
    - 114595 Bitumen
    - 114596 Oil-based hydrogen

Oil-based hydrogen is hydrogen produced from oil or oil products and intended for use in the energy sector. This category only applies to the hydrogen molecules that come directly from oil or oil products as raw materials; it does not apply to hydrogen produced through pathways using secondary energy carriers (electricity or heat) fuelled by oil or oil products.

The most common process for producing oil-based hydrogen is through steam methane reforming, first processing oil to produce methane; although some oil products (like naphtha) can be directly reformed. Other heavier oil compounds can be partially oxidised to produce hydrogen and carbon monoxide (Yuan *et al.*, 2005). Furthermore, oil and its products can also be auto-thermally reformed, wherein these hydrocarbons are made to react with steam and limited amounts of oxygen to produce hydrogen (Sadati Tilebon *et al.*, 2015).

⊞ 114597 Oil-based ammonia

Oil-based ammonia is ammonia produced from oil or its products. It is often a product of oil-based hydrogen.

⊟ 114599 Other oil products n.e.s.

⊟ 115000 Oil shale/sands

⊞ 119000 Other fossil fuels

Other fossil fuels refers to any other fossil fuels that, due to lack of detail, cannot be classified under any of the other groups.

⊞ 119100 Other primary fossil fuels

Other primary fossil fuels is a category made up of oils obtained by non-conventional production or any other primary fossil fuel that are not elsewhere specified.

⊞ 119200 Other fossil fuel products

Other fossil fuel products includes any secondary product coming from a source in the Other primary fossil fuels (119100) category.

⊞ 119900 Other fossil fuels n.e.s.

Other fossil fuels not elsewhere specified.

120000 NUCLEAR ENERGY

Nuclear energy is a category comprising uranium and plutonium, nucelar fusion fuels and other nuclear fuels. At present, almost all nuclear energy is produced from nuclear fission. Nuclear reactors use rods of nuclear fuel to create controlled chain reactions that generate heat. Carbon dioxide gas or water is pumped through the reactor to transport the heat away and use it to make steam and generate electricity. The most used nuclear fuel is uranium, but other nuclear fuels include plutonium, thorium and derived products.

The total energy supply from nuclear energy is the useful energy released during the nuclear reaction, measured as the enthalpy of the steam produced by the fission reaction. As with other thermal power plants, when steam is used to generate electricity, there will be differences (transformation losses) between the energy contained in the steam and the electricity produced. If there is no information about the steam's enthalpy, then the total energy supply is usually estimated to be three times the amount of electricity produced (*i.e.* assuming an efficiency of 33%), plus the amount of any heat taken directly from the reactor and used in other ways. Nuclear energy is often an important source of baseload power and can also be operated to co-produce heat.

121000 Uranium and plutonium

122000 Nuclear fusion fuels

Nuclear fusion fuels refer mainly to hydrogen isotopes required to power nuclear fusion, but may also include other fuels required in future technologies. This group includes deuterium (^{2}H), tritium (^{3}H), ^{3}He, ^{6}Li, and ^{11}B, among others.

129000 Other nuclear fuels

130000 NON-RENEWABLE WASTE

Non-renewable waste is an aggregate group comprising non-renewable industrial and municipal waste.

131000 Non-renewable industrial waste

Non-renewable industrial waste refers to waste materials from industrial activities that are used for energy purposes. Traditionally, used tyres, chemical waste and biohazardous waste are incinerated to produce electricity. Combustion may include co-firing with other fuels. The category does not include biomass waste from sectors such as forestry, agriculture, food processing and wood processing (covered under bioenergy), so all energy produced from industrial waste can be counted as non-renewable energy.

⚠ There is debate about the classification of tyres because many tyres are partially composed of natural rubber, which is a renewable feedstock. If known, this renewable energy content should be classified as renewable industrial waste (264200).

132000 Non-renewable municipal waste

Non-renewable municipal waste refers to waste materials from households, commerce and public services, often collected through municipal waste management processes.

⚠ Where detailed information about the non-renewable nature of municipal waste is not available, a statistical convention could be applied to assume that its energy content is 50% renewable and 50% non-renewable.

Waste is a primary source of energy that is burned to produce heat (for sale or direct use) or to generate electricity. It may also be processed into secondary fuels, such as refuse-derived fuel or solid recovered fuel, but these are not conventionally recorded separately in energy statistics. The organic part of waste could also be used to produce biogas, recorded as landfill biogas (263110) or other biogases from anaerobic digestion (263190).

140000 OTHER NON-RENEWABLE ENERGY

Other non-renewable energy includes heat from chemical processes and some energy produced from fuel cells. The category also includes any other energy carrier that is not renewable.

141000 Chemical heat

Chemical heat is the thermal energy produced by chemical reactions or dissolutions. Chemical heat is commonly used within the industry sector (own-use) or to produce electricity.

142000 Other non-renewable electrolytic hydrogen

Other non-renewable electrolytic hydrogen refers to hydrogen synthesised by water electrolysis powered by a non-renewable source not elsewhere specified in categories 110000, 120000 or 130000.

143000 Other non-renewable thermolytic hydrogen

Other non-renewable thermolytic hydrogen refers to hydrogen synthesised by water thermolysis (*i.e.* thermochemical water splitting) powered by a non-renewable source not elsewhere specified in categories 110000, 120000 or 130000.

144000 Other non-renewable ammonia

Other non-renewable ammonia refers to ammonia synthesised from electrolytic or thermolytic hydrogen that itself has been synthesised by a non-renewable source not elsewhere specified in categories 110000, 120000 or 130000.

149000 Other non-renewable energy n.e.s.

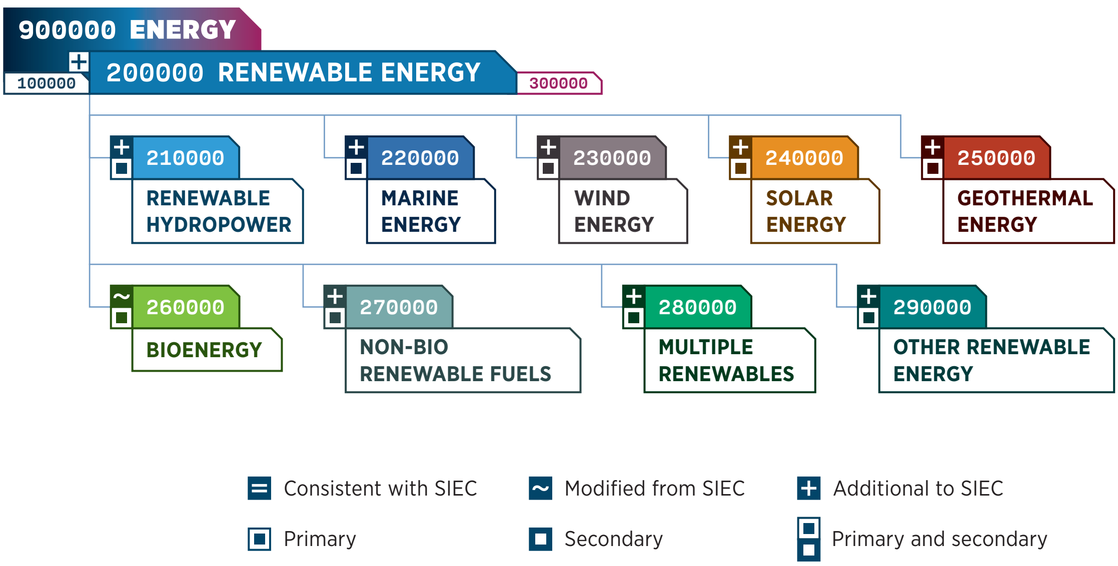
Other non-renewable energy not elsewhere specified are other energy sources counted as non-renewable energy that are not included in any other category and (a) for which the materials used in chemical reactions or as fuel for fuel cells are non-renewable resources or (b) that are produced using other types of non-renewable energy (*e.g.* natural gas used directly in fuel cells).

200000
RENEWABLE ENERGY

Renewable energy is an aggregate category, comprising renewable hydropower, marine energy, wind energy, solar energy, geothermal energy, bioenergy, non-bio renewable fuels, multiple renewables and other renewable energy, plus the electricity and heat generated from these sources.[5] These divisions are based on the various energy sources available in nature. Bioenergy is a component of renewable energy because it can be renewed or replaced in a relatively short cycle (compared with fossil fuels).[6] The other types of renewable energy are generated by converting natural forces such as flowing water, wind, solar radiation and naturally occurring heat into useful energy. The latter are renewable in the sense that their use does not reduce their availability in the future.

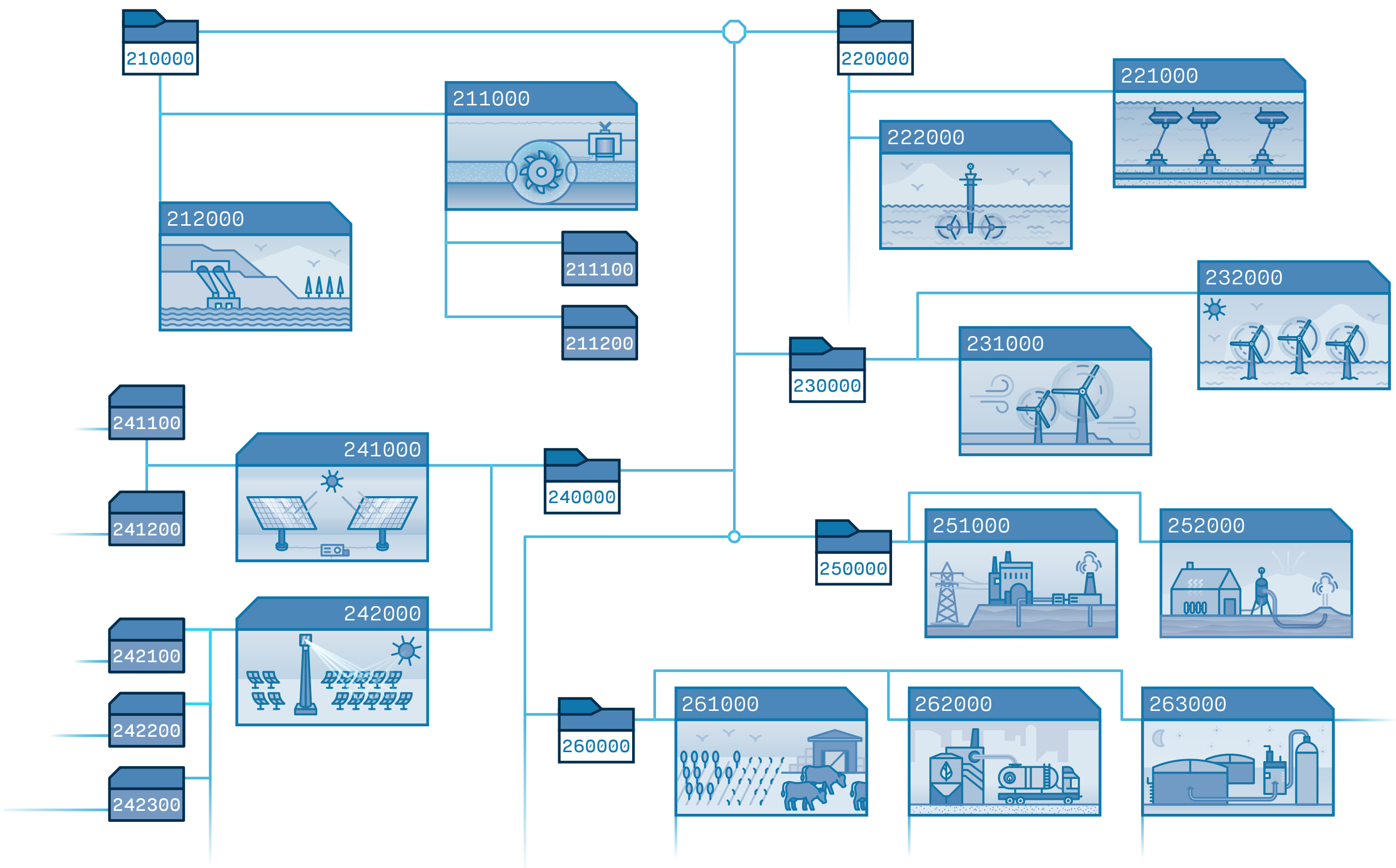
Many types of renewable energy produce electricity and heat directly; the total energy supply from these sources is the same as the amount of electricity and heat produced (*i.e.* unlike non-renewable energy sources, there are no transformation losses). However, there are differences between total energy supply and electricity production when electricity is generated from thermal processes, such as in concentrated solar power, geothermal energy and bioenergy.

Figure 7 IRENA classification of renewable energy



5 For hydropower, hydropower from pumped hydro is included in the total electricity production and capacity but excluded from the calculation of total renewable electricity generation.

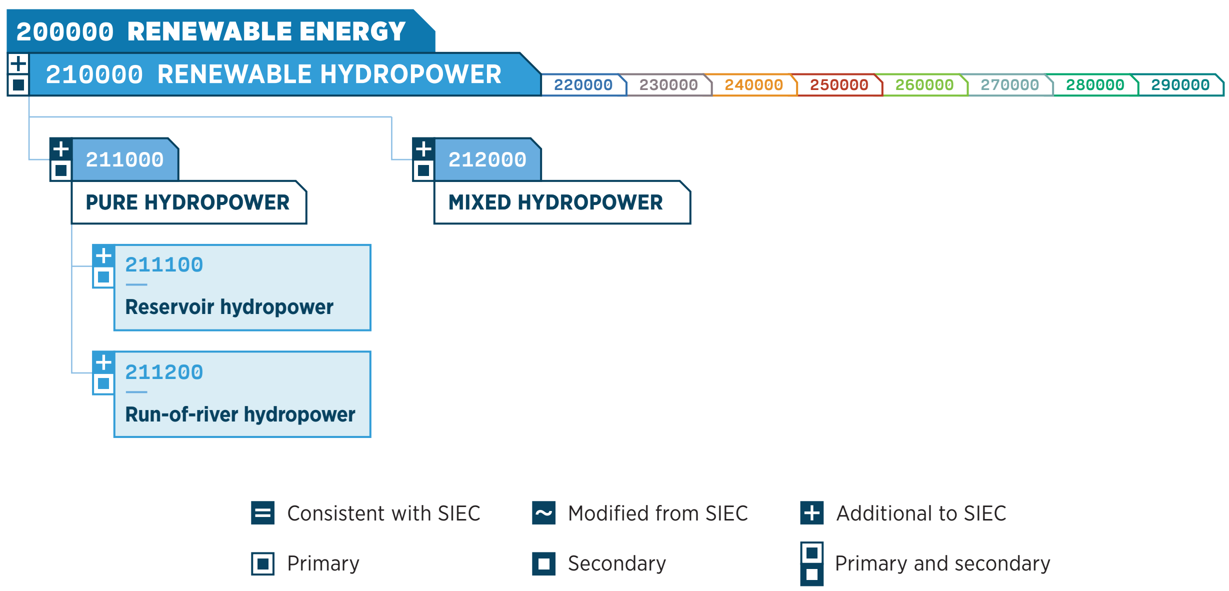
6 The sustainability of bioenergy is not part of the analysis for this taxonomy. But this sustainability is important to consider in the carbon cycle of bioenergy if the bioenergy sources are being consumed without replacement or at a much higher rate of replacement, thus eventually resulting in an unsustainable use of bioenergy.



210000 RENEWABLE HYDROPOWER

Renewable hydropower refers to the electrical energy generated from mechanical devices driven by flowing fresh water. These devices convert the freshwater's potential (reservoir hydropower) and kinetic (run-of-river) energy into electricity.

Figure 8 IRENA classification of renewable hydropower



⚠ Renewable hydropower is a primary source of energy, but it is only counted as primary at the point of electricity generation. The potential or kinetic energy of the water is not relevant because it falls out of scope of energy statistics.

Renewable hydropower is further subdivided into pure hydropower and mixed hydropower; mixed hydropower is combined with either pumped hydro or other electricity-generating technologies, and its operation is different from pure hydropower. Pure hydropower is divided into reservoir hydropower and run-of-river hydropower, which are distinct both in magnitude and in their potential to support the transmission grid's baseload power, as well as in their construction and electricity generation dynamics.

Renewable hydropower is considered a primary source of electricity, as the amount of total energy supply from hydropower is the same as the amount of electricity produced (UNSD, 2022). Much effort is ongoing in international energy statistics to ensure this principle, given that several official energy balances report the potential or kinetic energy of the water as the primary energy source. In those cases, there could be efficiency factors of around 85% or 90%, and it could vary by country.

IRENA's classification of renewable hydropower excludes direct uses of power derived from flowing fresh water (such as in water mills), power generated from flowing salt water (recorded as marine energy [220000]), and thermal energy extracted from fresh water (recorded as water-source heat pumps [292000]).

211000 Pure hydropower

Pure hydropower refers to the use of freshwater flow to generate electricity. Pure hydropower plants are typically located near natural sources of water, such as rivers, waterfalls or reservoirs, and can vary in size from small-scale run-of-river plants to large-scale facilities with significant storage capacity.

Two main methods capture the flow of water for hydropower production: (a) using dams to create reservoirs (reservoir hydropower) and (b) using the flow of water in rivers (run-of-river hydropower) or diverting part of the flow of a river into pipes leading to the hydropower plant (a second type of run-of-river hydropower). In-pipe or conduit hydropower, where flowing water in manufactured conduits or pipes is used for electricity generation, is uncommon and should only be counted as renewable energy if the water flows due to gravity rather than because it is pumped from elsewhere in the wider water network. If the water flow is due to pumping, any electricity generated should be treated as an improvement in energy efficiency (energy recovery) in the water distribution system rather than renewable electricity generation.

211100 Reservoir hydropower

Reservoir hydropower refers to electrical energy produced by fresh water that has been stored in reservoirs (dams or impoundments) at higher altitude than a turbine. This fresh water flows downstream through a turbine that turns a generator, producing electricity.

Reservoir hydropower operates with both constant and variable flow rates, depending on the characteristics of the water source. Constant flow plants are well suited for base load power generation; variable flow plants, which can adjust their output based on changes in water availability, can be used to provide peaking power or grid stabilisation services.

The overall cost of building and operating reservoir hydropower plants can vary widely, depending on factors such as the location and accessibility of the water source, the cost of materials and labour, the scale of the plant, and the cost of financing. In general, larger-scale plants have higher upfront costs but lower operating expenses than smaller plants.

211200 Run-of-river hydropower

Run-of-river hydropower plants transform the kinetic energy from flowing fresh water (usually from rivers) to generate electricity. Unlike reservoir hydropower plants, run-of-river plants do not require the construction of a large dam or reservoir to store water.

Instead, run-of-river plants typically use a small dam or diversion structure to redirect a portion of the river's flow through a penstock or channel, which leads to a turbine. As water flows through the turbine, it turns a generator to produce electricity, which can then be fed into the power grid or used on site.

One of the key advantages of run-of-river hydropower plants is their ability to generate electricity without significantly altering the natural flow of a river or stream nor significantly altering the landscape and impacting the local biodiversity, so long as they are not intensely developed (Kuriqi *et al.*, 2021). Additionally, run-of-river plants can often be built more quickly and with lower capital costs than reservoir hydropower plants (Amanda *et al.*, 2018).

212000 Mixed hydropower

Mixed hydropower plants combine naturally flowing water with pumped hydro or other technologies. Water can be pumped into reservoirs used only for this purpose (pure pumped hydro), or it can be combined with reservoir hydropower by pumping water into reservoirs that also capture naturally flowing water.

In both cases, electricity from flowing water that has previously been pumped into reservoirs is not counted as renewable energy but is subtracted from the amount of energy used for pumping, and the net energy consumption (because of this) is counted as own-use of electricity for the energy industry. During periods of low demand or excess generation from other renewable sources, such as wind or solar, the plant can use excess electricity to pump water uphill to the reservoir, effectively storing energy for later use. When demand increases or other renewable sources are not available, the stored water can be released to turn turbines and generate electricity.

⚠ In electricity generation statistics, production from mixed plants is divided into the proportion coming from naturally flowing water and the proportion coming from pumped hydro. The latter is counted as electricity generation from pumped hydro.

Mixed hydropower plants can also be designed to incorporate other forms of renewable energy, such as solar or wind, to further increase the overall output and efficiency of the plant. For example, a mixed hydropower plant may use solar panels (Silvério *et al.*, 2018) or wind turbines to provide supplemental electricity during periods of low water flow or reduced hydroelectric output. In such cases, only the electricity generated by hydropower is considered within the category of mixed hydropower.

Figure 9 Example of capacity and generation statistics showcasing mixed hydropower for Croatia, 2020-2022

	Electricity generation (GWh)			Electricity installed capacity (MW)		
	2020	2021	2022	2020	2021	2022
CROATIA	**13 385**	**15 210**		**4 662**	**4 873**	**4 962**
On-grid electricity	**13 385**	**15 210**		**4 662**	**4 873**	**4 962**
Total Non-Renewable	**4 835**	**4 683**		**1 407**	**1 383**	**1 369**
Fossil fuels	**4 687**	**4 582**		**1 407**	**1 383**	**1 369**
Natural gas	3 437	3 096				
Oil	34	29				
Coal and peat	1 215	1 457				
Fossil fuels n.e.s.				1 407	1 383	1 369
Pumped storage	**148**	**101**		NO CAPACITY		
Total Renewable	**8 551**	**10 528**		**3 255**	**3 490**	**3 593**
Hydropower (excl. pumped storage)	**5 662**	**7 128**		**2 200**	**2 201**	**2 201**
Renewable hydropower	5 662	7 128		1 924	1 925	1 925
Mixed hydro plants	NO GENERATION			275	275	275

Note: n.e.s. = not elsewhere specified.

Mixed hydropower plants should be recorded in installed capacity statistics as all the hydropower plants of any size that combine the production of hydropower from naturally flowing water with the production from pumped hydro. Conventionally, half the capacity should be attributed to mixed hydropower and the other half to pumped hydro. However, gross electricity generation should be recorded in pumped hydro, not in mixed hydropower.

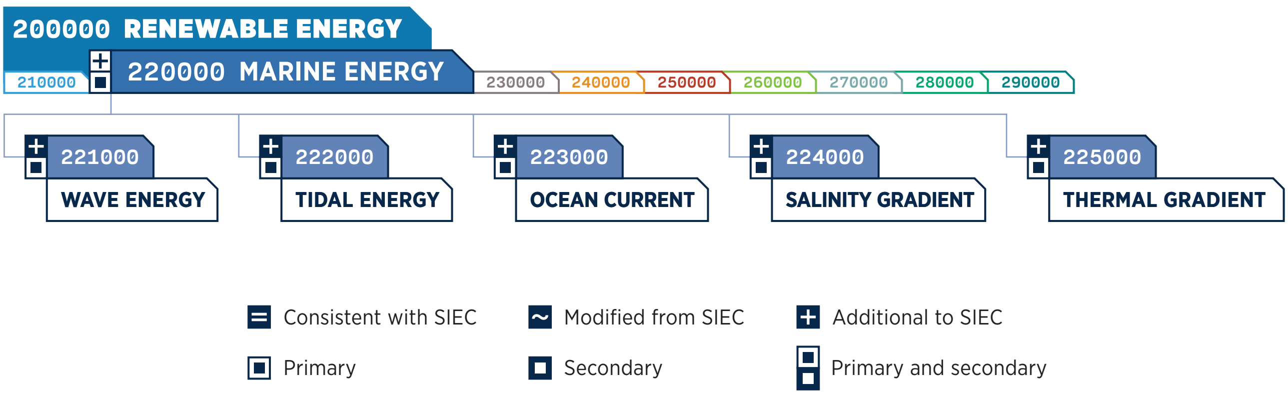
But capacity and generation are not always recorded in this way. The example shown in Figure 9 for Croatia shows how mixed hydropower plants and pumped hydro are interrelated yet recorded separately in Eurostat, and thus in IRENA statistics. Mixed hydropower shows 275 MW installed capacity, but no electricity generation. Pumped hydro, however, shows 0 MW of installed capacity but 148 GWh and 101 GWh of electricity generation. Instances like these are common across mixed hydropower plants and pumped hydro, showcasing a need to provide clearer guidelines on the classification of storage and the methodologies needed to account for them in energy statistics.

220000 MARINE ENERGY

Marine energy refers to the generation of electricity from devices driven by the movement of salt water, differences in saltwater temperatures, or salinity gradients. Most marine energy is currently derived from the mechanical energy in tidal movement, waves or ocean currents, so marine energy is sometimes called tide, wave or ocean energy.

The five divisions of marine energy are based on the type of energy conversion used to generate electricity or heat. The boundaries are clear for salinity gradient (224000), which uses the Gibbs free energy of mixing, and for thermal gradient (225000), which uses temperature potentials to produce thermal energy. The other three – wave energy (221000), tidal energy (222000), and ocean current (223000) – are determined by the mechanisms of deriving mechanical energy.

Figure 10 IRENA classification of marine energy



Marine energy excludes power generated from flowing fresh water, which is recorded as hydropower. Power generated from marine energy technologies placed in fresh water would also be classified as hydropower rather than marine energy. Marine energy also excludes wind power generated on offshore platforms (this is classified as offshore wind energy) and thermal energy derived from salt water and used for heating or cooling (this is recorded as energy from water-source heat pumps), but it does include thermal energy derived from salt water used to generate electricity.

A wide range of devices are used to generate electricity from marine energy; when that electricity is generated from mechanical forces, it is considered a primary source of electricity (*i.e.* the total energy supply equals the amount of electricity produced). Other forms of marine energy result in transformation losses in the production of electricity, so the total energy supply will be more than the amount of electricity produced.

At present, the production of marine energy is relatively small, so it is not yet recorded in different subcategories in IRENA's renewable energy statistics. However, the differences between the main types of marine energy are included in this taxonomy for future use.

⊞ 221000 Wave energy

Wave energy refers to electricity produced from devices driven by the motion of waves. The energy content depends on the speed, height, frequency and density of the wave. Wave energy produces electricity intermittently, either close to land or in the open ocean.

Most wave energy conversion technologies use floating devices that may or may not be anchored to the seabed. These devices move up and down with the waves, using this movement to push water or compressed air through turbines or convert the fluids' momentum into rotational motion through rack and pinion mechanisms. Other wave energy converters include devices that capture the water at the tops of waves to create short-term differences in water levels (and use this to drive water turbines) and devices on the seabed that use differences in water pressure to drive turbines as waves pass over them.

Specific technologies used to harvest wave energy include (a) point absorbers, which are floating buoys; (b) oscillating wave surge converters, which use an oscillating flap to capture energy while mounted on the seabed; and (c) oscillating water columns, which are partially submerged, hollow columns that compress air pockets through an air turbine (Rehman *et al.*, 2023).

⊞ 222000 Tidal energy

Tidal energy is the kinetic energy harnessed from the tides: ocean water moving vertically due to the gravitational pull of the sun and of the moon and those pulls' interactions with Earth's gravitational field. Tides occur twice a day and depend on the Earth's location and position. Tidal energy can be subdivided into (a) rise and fall tides and (b) ebb and flood currents. Tidal energy is generated close to the coastline. Tidal energy is predictable and is a constant source of energy suitable for producing baseload power. As of the early 2020s, this technology is still in its infancy (Chowdhury *et al.*, 2021).

⊞ 223000 Ocean current

Ocean current energy refers to the kinetic energy included in the continuous flows of ocean waters, usually in shallow water and driven by wind flows, density changes, salinity and temperature, with the water flowing in one direction either permanently or over long periods of time.

Ocean current energy is typically generated far from land (more than 20 km away from shore), at typical depths over 500 m (Neill, 2022), and is a constant source of energy suitable for baseload electricity generation. In theory, ebb and flood currents are within the scope of ocean currents, but IRENA categorises them as tidal energy (222000) due to their proximity to land.

224000 Salinity gradient

Salinity gradient refers to electrical energy produced by the Gibbs free energy of mixing. This phenomenon occurs when two different solutions mix. In this case, the two solutions are fresh water and salt water, for which the main difference is their salinity concentration.

The two main mechanisms for generating salinity gradient energy are pressure-retarded osmosis and reversed electrodialysis (Neill, 2022). In pressure-retarded osmosis, water with a low salt content moves through membranes through osmotic permeation to reduce the salinity of salt water on the other side of the membranes and then expands inside a turbine to generate electricity (Ramon *et al.*, 2011). In reversed electrodialysis, the ions in salt water are used to generate an electric charge (Nijmeijer and Metz, 2010), which can be used as electricity. Other mechanisms for capturing and using these forces, such as capacity mixing, are also being researched (Yip *et al.*, 2016).

Salinity gradient is especially useful where rivers connect to the open ocean. Salinity gradient electricity generation has transformation losses, so total energy supply and electricity production will differ. However, the efficiency of such systems is usually high, at around 90% for pressure-retarded osmosis (Yip and Elimelech, 2012).

225000 Thermal gradient

Thermal gradient energy, also known as ocean thermal energy conversion, is the energy that can be harnessed from the thermal difference between cold deep seawater and warmer surface water with a difference of at least 20°C. An organic Rankine thermodynamic cycle can generate electricity using heat transfer between these two water flows (Yang and Yeh, 2014). Thermal gradient power is more suitable in places where surface water gets warmer than colder deeper water, such as in tropical regions (Avery and Wu, 1994).

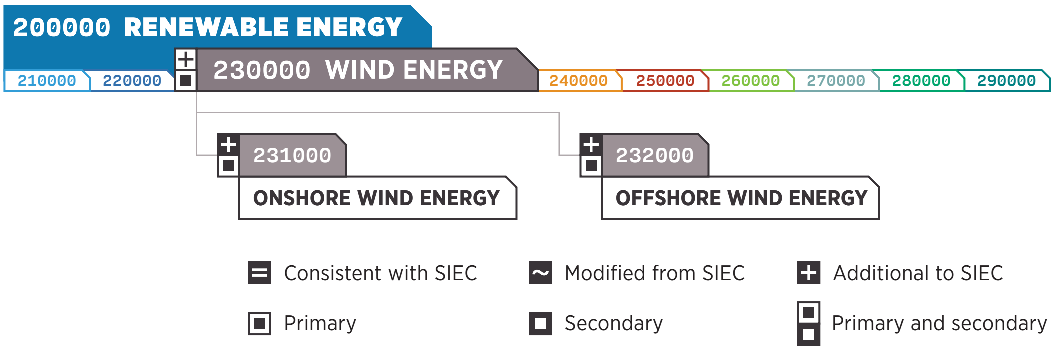
As ocean thermal energy conversion systems use thermal energy to generate electricity, there are transformation losses in the system, and the amount of primary energy supplied will be more than the amount of electricity generated. There is, at present, no generally accepted estimate of what the efficiency of such systems might be, but it is expected to be relatively low (under 5%).

230000 WIND ENERGY

Wind energy is the kinetic energy of airflow that is transformed into useful energy (mostly electrical energy). Wind energy is produced using a range of mechanical devices, such as wind turbines, sails, airfoils and kites. The scale of wind energy production ranges from large collections of megawatt-scale turbines (wind farms) to small devices with a capacity of only a few kilowatts or less.

The divisions of wind energy are based on their geographical placement: on land for onshore wind, and on water (particularly salt water) for offshore wind. More fundamentally, this division reflects a stark difference in kinetic wind energy potential that can be converted into electricity: winds that flow over oceans are more energy dense than those that flow over land.

Figure 11 IRENA classification of wind energy



Wind energy is a primary source of energy. IRENA recommends following the IRES principles for wind energy statistics, where the amount of total energy supply is the same as the amount of electricity produced, rather than the kinetic energy content of the wind itself. Wind energy is also a variable source of energy that is usually integrated into national electricity supply systems (national grids). Where wind energy is produced off grid, it is often combined with an energy storage system, and it may be combined with other types of electricity generation (*e.g.* hybrid wind and diesel generation). In such cases, only the proportion of electricity generated from wind should be counted as wind energy.

231000 Onshore wind energy

Onshore wind energy is electricity generated from the wind by devices located on land. It includes wind energy produced from devices installed on piers, platforms, breakwaters or other artificial structures, if those structures are connected to the land in any way. It also includes production from devices located in rivers and inland water bodies, where these do not fit the definition of offshore wind energy.

Onshore wind farms typically consist of multiple turbines installed in areas with high average wind speeds, such as hilltops or open plains. The turbines used in onshore wind energy are typically large, multi-bladed structures that rotate when wind passes over the blades. The motion of the blades drives a generator, which produces electricity that can be fed into the power grid or used on site. Other designs also exist, including oscillating vertical bars.

Onshore wind energy systems vary considerably in size and in type of use. There are also small wind generators of a few kilowatts that are commonly used in residential areas or on microgrids. Micro wind turbines of a few watts are also used to power small appliances or charge batteries.

232000 Offshore wind energy

Offshore wind energy is electricity generated from the wind by devices located in water. It includes energy from all devices placed in salt water, including devices installed on floating platforms as well as those placed on structures that have foundations permanently covered by salt water. It also includes energy from devices placed in fresh water, where the technologies and operational practices are similar to those used for devices placed in salt water.[7] It does not include energy from devices installed on piers, platforms, breakwaters or other artificial structures, if those structures are connected to the land in any way.

Offshore wind energy requires specialised technology and infrastructure to support the turbines in marine environments. Offshore wind turbines are typically larger and more powerful than onshore turbines and are designed to withstand harsh weather conditions and the corrosive effects of salt water. They are typically mounted on floating platforms or fixed foundations and are connected to the onshore power grid using underwater cables.

240000 SOLAR ENERGY

Solar energy refers to the production of electricity and heat from solar irradiation. It includes the direct conversion of solar irradiation into electricity through photovoltaic processes and the active use of solar radiation to produce heat. This heat can be used directly or sold to others, or it can be used to generate electricity in a thermal power plant (concentrated solar power).

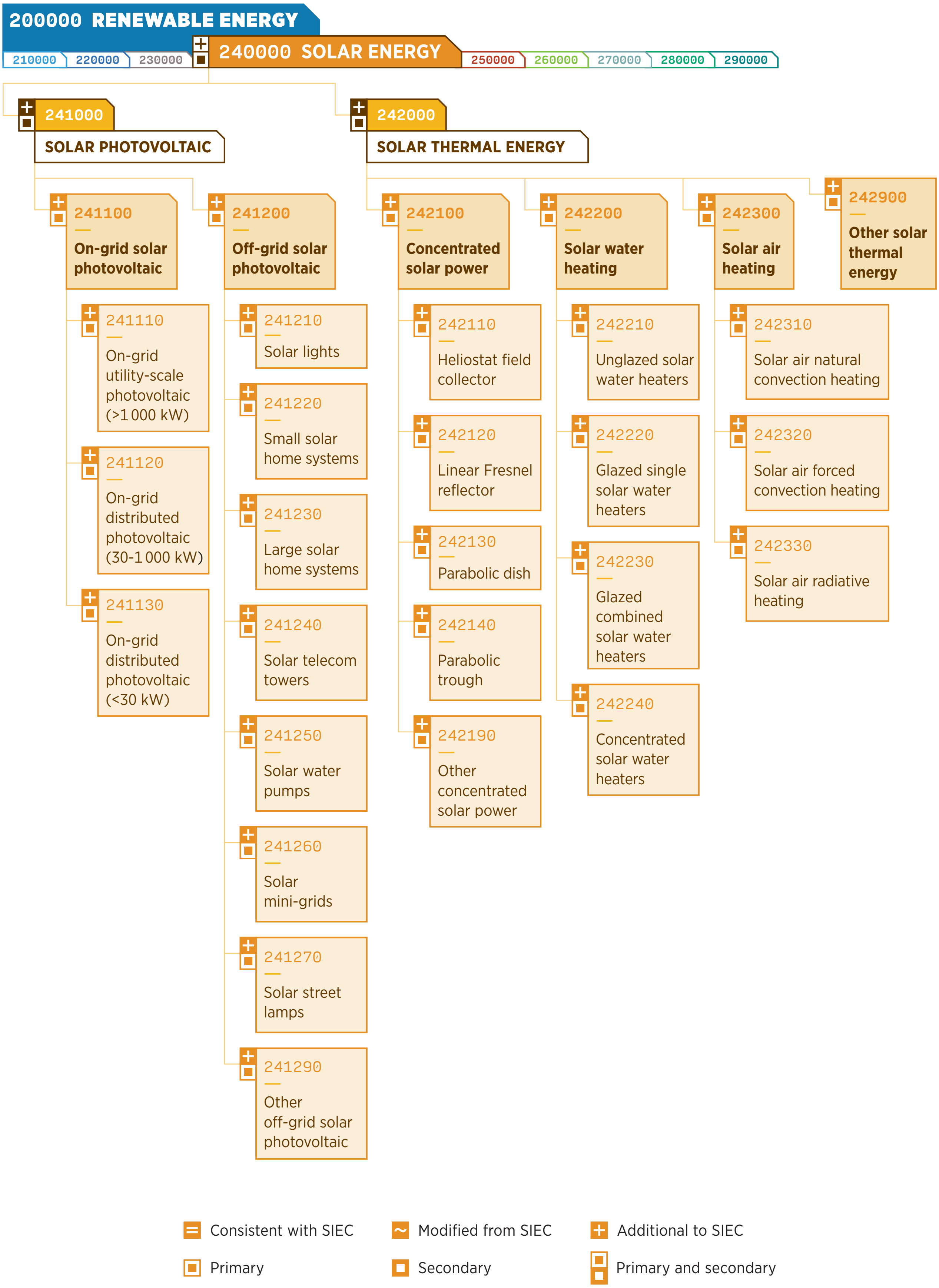
Solar energy includes all electricity generated from solar irradiation (photovoltaic and concentrated solar power) and the active production of heat with the use of solar thermal collectors. Solar thermal collectors are devices specifically designed to focus and/or absorb solar radiation and transfer it to another medium (usually water or air). These devices can use fans, pumps, glazed panels, mirrors or other mechanical devices to capture or concentrate solar energy or facilitate the movement of heat from one place to another.

The distinction between active and passive solar energy is that the latter does not use mechanical devices apart from switches to open or close valves and vents and prevent the movement of heat in the wrong direction.

⚠ Solar energy excludes passive uses of solar irradiation, such as in evaporation ponds or greenhouses or from the transfer of heat into or out of buildings through non-mechanical architectural features designed to capture and use solar irradiation.

[7] *For example, energy from wind turbines located in the Great Lakes of North America would be classified as offshore wind energy if the turbines were operated in the same way as turbines installed in the ocean.*

Figure 12 IRENA classification of solar energy



Solar energy excludes heat production in air-source heat pumps since it is considered passive energy and thus falls outside of the scope of energy statistics.[8]

Solar irradiance can be classified as direct, diffused or reflected. Each type of irradiance has specific uses, and the amount of irradiation varies depending on weather conditions, geographical locations, and the Earth's location relative to the sun, among other factors. Solar irradiance is measured in watts per square metre (W/m^2). It can range from 0 W/m^2 during night-time and bad weather conditions to 1 000 W/m^2 at sea level during clear skies and to almost 1 400 W/m^2 outside the Earth's atmosphere (Coddington *et al.*, 2016).

Solar energy can be categorised into solar photovoltaic and solar thermal energy; this division is based on the thermodynamical mechanisms used to derive energy from the solar irradiance. Solar thermal energy further splits into concentrated solar power, solar water heating, solar air heating and other solar thermal energy based on how the thermal energy is used in the energy sector. Both solar photovoltaic and concentrated solar power generate electricity, while other solar energy types actively produce thermal energy from solar irradiation. If solar energy is generated in hybrid plants with fossil fuels or other technologies, the energy from each energy source should be accounted for separately under its appropriate category.

For other solar energy types, the total energy supply and the thermal energy production are the same at the collector, although energy losses may occur in the distribution network.

⚠ If thermal energy production is not measured at the collector (*e.g.* if it is measured as heat sold in a district heating system), the total energy supply is assumed to be equal to the thermal energy produced.

Off-grid solar energy production is often combined with an energy storage system and may integrate with other electricity generation (*e.g.* hybrid solar and diesel generation). In such cases, to use the solar-diesel example, only the proportion of electricity generated from solar should be counted as solar energy, and the electricity from diesel should categorised within fossil fuels.

⊞ 241000 Solar photovoltaic

Solar photovoltaic (PV) energy refers to the electricity generated through the direct conversion of solar irradiation into electricity via the PV effect in semiconductor devices, such as solar cells. Solar cells can be arranged together as solar panels and panels can be arranged as arrays.

Solar PV is either connected to an electricity grid or not. Due to energy access and grid operation planning, the IRENA categorisation subdivides solar PV into on-grid solar PV (241100) and off-grid solar PV (241200).

[8] *Solar thermal collectors operate in a way that is very similar to air-source heat pumps, but these two types of device can be distinguished by the medium used for heat transfer. Heat pumps use fluids with low boiling points to absorb ambient heat from an external environment are not dependent on solar radiation as a heat source. Energy from such devices should be classified as coming from air-source heat pumps rather than as solar energy.*

⚠ Solar PV capacity should be recorded as net capacity, which is in alternating current terms. But much off-grid PV energy is recorded in direct current terms, as the electricity produced might be directly used without inverters or electricity injection into the grid.

Solar PV devices may also integrate mechanisms, known as concentrator PV devices, to focus or concentrate solar irradiation onto solar cells, thus increasing their electricity output. High-concentration PV devices may also need cooling mechanisms for the solar cells (Gharzi *et al.*, 2020). While electricity production from high-concentration PV devices may resemble concentrated solar power generation, it is classified as solar PV energy. But any useful heat recovered from cooling water in such devices should be counted in the appropriate subcategory under solar thermal energy (242000).

244100 On-grid solar photovoltaic

On-grid solar photovoltaic are solar photovoltaic panels, systems and arrays connected to the distribution or transmission grid. This is an aggregate group comprising different set-ups of solar photovoltaic divided by size and/or by connection type to the grid.

241110 On-grid utility-scale photovoltaic (<1 000 kW)

On-grid utility-scale photovoltaic are solar photovoltaic systems that produce electricity for the transmission grid and that have the sole economic purpose of producing electricity. As such, this excludes any solar photovoltaic systems that are connected to the transmission or distribution grids and produce net electricity but that have a different economic activity (*i.e.* an activity other than producing electricity). On-grid utility-scale photovoltaic typically has an installed capacity of 1 000 kW or more and is usually located in large open areas like deserts, farmland and lakes.

241120 On-grid distributed photovoltaic (30-1 000 kW)

On-grid distributed photovoltaic (30-1 000 kW) includes solar photovoltaic systems designed for on-site electricity generation and consumption that are typically connected to the distribution grids to sell any excess electricity generated. These systems are typically installed on commercial and public buildings and range in size from 30 kW to less than 1 000 kW.

⚠ Where on-grid distributed photovoltaic is in place, capacity statistics should record the net installed capacity of the panels in alternating current terms, electricity generation should reflect the gross generation of the panels, and energy balances should include the gross generation and consumption of electricity in its respective energy sector (*e.g.* households, commerce and public sector, or industry).

Distributed photovoltaic systems are often installed for the purpose of reducing electricity bills and increasing energy independence, particularly in regions with elevated levels of solar irradiation and high electricity costs. These systems can also be used to provide backup power in the event of grid outages and can help reduce greenhouse gas emissions by offsetting on-site electricity use.

Users who generate excess electricity might sell it back to the utility through net metering or feed-in tariffs, where these policies are in place. On-grid distributed photovoltaic (30-1 000 kW) systems can also operate independently of the grid as stand-alone off-grid panels. In some cases, distributed photovoltaic systems of this size may also be integrated with energy storage systems, such as batteries, to provide a more stable and reliable source of electricity (El-Ela *et al.*, 2021).

In addition to commercial applications, on-grid distributed photovoltaic systems of this size might be installed at industrial sites to produce hydrogen or other synthetic chemicals.

241130 On-grid distributed photovoltaic (<30 kW)

On-grid distributed photovoltaic (<30 kW) includes solar photovoltaic systems designed for on-site electricity generation and consumption that are usually connected to the distribution grids to sell any excess electricity generated. These systems are typically installed on residential and other small buildings, and are sized at less than 30 kW.

In numerous instances, these systems are reported in energy statistics to reflect the implementation of net metering schemes in households and commercial and public buildings.

241200 Off-grid solar photovoltaic

Off-grid solar photovoltaic is an aggregate group of off-grid solar photovoltaic systems and technologies that are not connected to a distribution or transmission grid. These subcategories are segmented by type of system or technology, and solar lights (241210), small solar home systems (241220), large solar home systems (241230), and solar mini-grids (241260) also line up with the tiers of electricity access specified by ESMAP (Energy Sector Management Assistance Program) in its Multi-Tier Framework for Measuring Access to Electricity.

241210 Solar lights

Solar lights, also known as solar-powered lights or solar lamps, are lighting fixtures that (a) use PV solar panels to generate electricity from sunlight and store that electricity in rechargeable batteries and (b) have installed capacities of less than 11 W. They typically consist of a small LED light, a solar panel and rechargeable batteries (Sunmaster, n.d.). Solar lights are designed to be portable and easy to use and can be set up and moved around as needed. They are often used in areas where electricity is not readily available or reliable, and they often provide energy access solutions to rural households.

⚠ For off-grid solar PV, IRENA has tried to match ESMAP's electricity access tiers, although the categories may overlap.

Tier 0-1: Solar lights
Tier 1: Small solar home systems
Tier 2: Large solar home systems
Tier 2+: Solar mini-grids

Solar lights usually produce low-intensity ambient light rather than bright, focused light. One of the main advantages of solar lights is their low cost and ease of installation, as they do not require any wiring or electrical connections.

241220 Small solar home systems

A small solar home system, also known as a solar kit, is a stand-alone solar-powered system designed to provide electricity to households in areas with limited or no access to the grid. Small solar home systems typically have a power output of between 11 W and 50 W and include solar panels, a battery bank, a charge controller and an inverter (MicroEnergy International GmbH, 2014).

The solar panels produce direct current electricity, often stored in batteries and protected by the charge controller to avoid overcharging or damaging the batteries. Then, the inverter converts the direct current electricity into alternating current electricity, which can be used to power household appliances (Salas, 2017).

Small solar home systems are becoming an increasingly popular and effective solution for off-grid electricity needs in many parts of the world (IRENA, 2022a), increasing household daily light uses and reducing the usage of fossil fuel-based lamps (Wagner *et al.*, 2021), as well as other spillover welfare benefits (Diallo and Moussa, 2020).

241230 Large solar home systems

Large solar home systems include all solar home systems with an installed capacity greater than 50 W. These systems can typically support larger home appliances, such as refrigerators, fans and televisions. Solar home systems with a capacity greater than 50 W typically include larger solar panels, a larger battery bank, a charge controller and an inverter. Large solar home systems can be helpful for electricity demand in off-grid households, extending beyond basic lighting.

241240 Solar telecom towers

Solar telecom towers are solar PV systems designed exclusively to power telecommunication towers in isolated regions that are not connected to the grid, such as those located on mountain hills. Solar telecom towers usually replace or complement the use of diesel generators, which require frequent maintenance and refuelling. In many cases, solar-powered telecom towers can also provide a more stable and consistent source of electricity (Singh and Avikal, 2020), which can help improve the quality and reliability of communication services in remote or off-grid areas (Deevela *et al.*, 2021).

241250 Solar water pumps

Solar water pumps are water pumps exclusively powered by electricity from solar panels. Most such pumps have solar panels feeding an electric motor that turns a bore or surface pump. The pump moves underground or stream water to either a storage tank for later water use (reducing the need for energy storage or further pumping of water [CTCN, 2016]) or directly to its required end use.

Solar water pumps are mostly used in the agricultural sector, to irrigate land and crops, thus replacing the use of electricity from the grid, diesel generators or manually carried water.

There are two main types of solar water pump: submersible and surface. Submersible solar water pumps extract water from underground, using wells or boreholes (Aminata *et al.*, 2020). Surface solar water pumps draw water from rivers or streams.

241260 Solar mini-grids

Solar mini-grids are larger solar arrays that connect multiple demand nodes, such as households, creating a small electricity distribution grid. These systems typically comprise a solar array, a battery bank, an inverter and a distribution system (Zajicek, n.d.).

Solar mini-grids cater to small or remote populations (Asuamah *et al.*, 2021) when solar home systems are insufficient for larger electricity needs. Solar mini-grids can operate separately from national grids, using solar energy as their primary source for electricity generation.

241270 Solar street lamps

Solar street lamps are outdoor lighting units entirely powered by solar energy. Typically, they include solar panels, a battery, an LED lamp and a control system. Solar street lamps usually operate at night or during dark weather conditions, using stored electricity from the solar panels.

In energy statistics, the installed capacity of the solar panels should be used, rather than the light output of the lamp (measured in lumens), which can vary depending on the efficiency of the LED lamp and the design of the lighting fixture (Aung and Myint, 2014).

241290 Other off-grid solar photovoltaic

Other off-grid solar photovoltaic is a category that includes photovoltaic products that provide power for a wide variety of end uses, such as industrial facilities, solar fridges, electrification of schools and clinics, and private commercial developments in the retail and tourism sectors. This category is not exhaustive and represents off-grid photovoltaic products not elsewhere specified.

242000 Solar thermal energy

Solar thermal energy is an aggregate group that includes concentrated solar power, solar water heating, solar air heating, and other solar thermal energy.

242100 Concentrated solar power

Concentrated solar power is the production of electricity, and potentially heat, from systems that use lenses or mirrors and tracking devices to concentrate a large area of solar irradiance into a smaller area. These systems operate through heat exchangers that use the concentrated irradiance to heat a working fluid that evaporates water into steam of different pressures. The pressurised steam expands through a turbine, which turns an electricity generator.

A wide range of concentrating technologies exist, each with different ranges of operating temperatures, different mechanisms and different technology maturity. The subcategories are based on these differences. Subcategories could be added for new technologies as they are designed and implemented across countries in the future.

Table 2 Technical aspects of concentrated solar power technologies

Technology	Geometry	Tracking	Operating temperature (°C)
Heliostat field collector	Point	2 axis	150-2000
Parabolic dish reflector	Point	2 axis	100-500
Linear Fresnel reflector	Tubular	1 axis	60-250
Parabolic trough collector	Tubular	1 axis	60-800

Source: Haurant, 2019.

Concentrated solar power is usually generated at a relatively large scale and, although it is a variable source of energy, it is often combined with heat storage devices so that it can generate electricity more predictably and during the night.

The total energy supply used in concentrated solar power is the energy content of the steam used to produce electricity. If the energy content of the steam is not measured directly, it can be derived from the amount of electricity produced, often assuming a thermal efficiency of 33%.

Concentrated solar power may also include the production of useful heat from combined heat and power production. In such cases, this heat is recorded as heat production.

242110 Heliostat field collector

Heliostat field collectors, or solar tower collectors, are concentrated solar power plants that use a series of mirrors, known as heliostats, to direct sunlight towards a central tower. The tower absorbs the radiative heat from the sunlight, raising the temperature of a thermal fluid, typically molten salts, to up to 2000°C. The heated molten salts transfer heat to water, evaporating it into superheated steam, which drives a turbine to generate electricity.

Heliostat field collectors can be used for power generation and industrial applications because of the high temperatures they can reach (Gadalla and Saghafifar, 2018).

242120 Linear Fresnel reflector

Linear Fresnel reflectors are concentrated solar power plants that use long, flat, rectangular mirrors (reflectors) with a single-axis sun-tracking mechanism. These mirrors focus solar radiative heat onto fixed receivers (tubes) positioned above them, allowing for greater mirror mobility when tracking the sun. Employing the Fresnel lens effect, the concentrating mirrors are designed with a large aperture and short focal length, reducing the light absorption, volume and mass of the mirror. Multiple receivers are mounted on trackers to adjust the mirror angles for optimal reflection, which lowers costs and enhances system efficiency (Barbón *et al.*, 2021; Pulido-Iparraguirre *et al.*, 2019; Vouros *et al.*, 2019).

The receivers contain a working fluid that, when heated, can heat water and/or evaporate it to generate steam.

The main advantages of linear Fresnel reflectors are their simplicity, robustness, low wind load due to the reflectors being placed close to the ground (Mills, 2012), low capital costs, and flexibility of design (Kedare and Desai, 2017). These systems' working fluid can reach temperatures of around 250°C, making them useful for electricity generation and lower thermal demand uses such as distributed heating networks.

242130 Parabolic dish

A parabolic dish comprises a dish-shaped mirror constructed from numerous smaller flat mirrors that focus and concentrate sunlight onto a thermal receiver (tube), often coupled with a solar Stirling engine (Hafez *et al.*, 2017).

The reflectors are commonly mounted on a sun-tracking system to maximise the absorption of irradiance. A Stirling dish is the most common design for these systems and functions by heating a working fluid (typically hydrogen or helium) inside the thermal receiver, which in turn expands to push pistons, generating mechanical energy that drives an electricity generator (Kumar *et al.*, 2022).

242140 Parabolic trough

A parabolic trough is a type of solar thermal energy system that uses a series of long, curved (parabolic) mirrors to concentrate sunlight onto a focal line, where a receiver tube is placed. This design efficiently captures and focuses sunlight, using the geometric properties of the parabolic shape. The mirrors are usually made of glass, with a reflective coating or film to maximise reflectivity. The receiver tube is positioned along the focal line of the parabolic mirrors, absorbing the concentrated sunlight. The receiver tube typically contains a heat transfer fluid, such as synthetic oil, water or molten salts, that absorbs heat and transfers it to water for heating or evaporation into steam (Bellos, 2019), thereby driving a turbine, which is connected to a generator that produces electricity. The entire parabolic trough collector assembly is mounted on a tracking system that follows the sun's movement.

Parabolic trough collectors can achieve temperatures of up to 800°C (Krishna *et al.*, 2020), making them suitable for power generation and various industrial processes. They are often used in large-scale solar thermal power plants and can be combined with thermal energy storage systems, allowing them to produce electricity even during the night or when direct solar irradiance is blocked due to weather conditions (Strasser, 2023). Parabolic trough collectors are the most common linear concentrating system (Goel *et al.*, 2020).

242190 Other concentrated solar power

Other concentrated solar power not elsewhere specified.

242200 Solar water heating

Solar water heating involves converting the radiative thermal energy from sunlight into thermal energy that can be used for domestic water heating. This group is divided into the main thermodynamic processes for solar water heating.

Solar water heaters (SWHs) have collectors that absorb the energy from the sun and transfer it to a heat transfer fluid. The heated fluid transfers heat to the domestic water.

Solar water heating systems typically supply between 50% and 80% of the annual hot water requirements for a household and can greatly reduce the amount of electricity or gas needed for water heating (Artur *et al.*, 2020; Faisal Ahmed *et al.*, 2021; Giglio *et al.*, 2019; Pomianowski *et al.*, 2020). They are most effective in areas with a high level of solar irradiance and a significant demand for hot water, and they are widely used in residential, commercial and industrial settings (Weiss and Spörk-Dür, 2023).

To account for solar water heating in installed capacity statistics, the capacity of the solar collectors (often measured in square metres) is typically used as the basis for measurement, while thermal power is also useful (measured in MW_{th}). In energy balances, solar water heating is estimated as a form of energy consumption for households or the commercial and public sector. Total energy supply (solar thermal energy) and thermal energy generation are the same at the collector (100% efficiency), but energy losses may occur in the distribution network. These losses should be considered if thermal energy generation is not measured at the collector (*e.g.* if it is measured as heat sold in a district heating system). Otherwise, the total energy supply is assumed to be 100% of the thermal energy produced.

⊞ 242210 Unglazed solar water heaters

Unglazed SWHs use a black mat or a series of black tubes to absorb sunlight and heat water as it circulates through the system. Unglazed SWHs are primarily used for heating outdoor swimming pools and are less efficient than glazed SWHs.

In installed capacity statistics, unglazed SWHs are typically reported separately from glazed SWHs due to their different applications and efficiencies (Wang *et al.*, 2018).

⊞ 242220 Glazed single solar water heaters

Glazed single SWHs are solar water heating systems that consist of a solar collector with a transparent glazed cover and, often, an insulated storage tank. The collector is typically made of copper or aluminium and contains a dark absorber plate that absorbs solar radiation heat (Wang *et al.*, 2018).

Glazed single SWHs are typically more efficient than unglazed systems because the glazed cover creates an insulation layer, reducing heat losses from the collector. They are regularly used in residential and commercial buildings for domestic water heating.

⊞ 242230 Glazed combined solar water heaters

Glazed combined SWHs are solar water heating systems that consist of more than one solar collector with a transparent glazed cover and, often, one or more insulated storage tanks. By using multiple glazed collectors, the thermal efficiency of water heating increases compared to using a single SWH. The flow dynamics could be vastly different than in single collectors: the heating fluid could flow from one collector to another (connected in series) or it could flow through each collector once and then mix (connected in parallel).

Glazed combined SWHs are more ideally used for large-scale water heating in commercial buildings.

⊞ 242240 Concentrated solar water heaters

Concentrated SWHs use mirrors or lenses to concentrate sunlight, increasing the intensity of solar irradiance. The concentrated sunlight is then used to heat a fluid, which is typically water used for domestic or industrial purposes. The heated water is stored in an insulated tank and used as needed, and the system may be designed to include backup heating sources in case of cloudy weather.

Concentrated SWHs can be more thermally efficient than other solar water heating systems because they capture more solar energy using the same surface area. However, they can also be more complex and expensive to install and maintain.

242300 Solar air heating

Solar air heating refers to the use of solar thermal energy to heat air. The heated air can be used for domestic space heating, ventilation heating, industrial process heating or agricultural drying (Solar Air Heating Organization, 2015). Solar air heating systems typically consist of a collector panel, which absorbs sunlight and heats the air, and potentially a mechanism for circulating the heated air into a building or process.

There are three main types of solar air heating process: natural convection, forced convection and radiative heating.

242310 Solar air natural convection heating

Solar air natural convection heating refers to the use of solar thermal collectors to heat air, which in turn flows through a thermodynamic system by natural convection. In natural convection, as the solar energy heats the air, the air expands and becomes less dense, rising naturally and flowing up through vents into the space to be heated. As the air cools, it contracts and becomes denser, sinking and returning to the collector to be heated again (NREL, n.d.). This makes solar air natural convection heating an energy-efficient and cost-effective option for heating small spaces with good ventilation (*e.g.* greenhouses or small rooms) and low space heating demand.

In terms of energy statistics, solar air natural convection heating falls under the category of solar thermal energy and contributes to the overall renewable energy generation in a given area.

242320 Solar air forced convection heating

Solar air forced convection heating refers to the use of solar thermal collectors to heat air, which in turn flows through a thermodynamic system by forced convection. In forced convection, a compressor pushes air through the solar thermal collectors, which heat the air as it passes through them; the air flows onward to heat a space or reduce the humidity of a space or substance.

This method is particularly useful for larger spaces or agro-industrial applications where the heat demand is larger than can be supplied by natural convection systems (Vadiee, 2022).

242330 Solar air radiative heating

Solar air radiative heating refers to the use of solar radiation to heat a surface, which in turn heats air in contact with the surface, usually in thermal isolation from the environment. Various surfaces can be used, including black-painted metal plates or ceramic tiles, all of which are selected for their high capacity to absorb solar radiation energy. The heated surface is placed in a container with a glass cover, which allows solar radiation to pass through the glass and to the surface material while trapping the heated air inside. This heated air can be used for space heating, industrial process heating, or agricultural drying (NREL and US DOE, 2001).

In energy statistics, solar air radiative heating falls under the category of solar thermal energy and contributes to the direct use of solar thermal energy.

242900 Other solar thermal energy

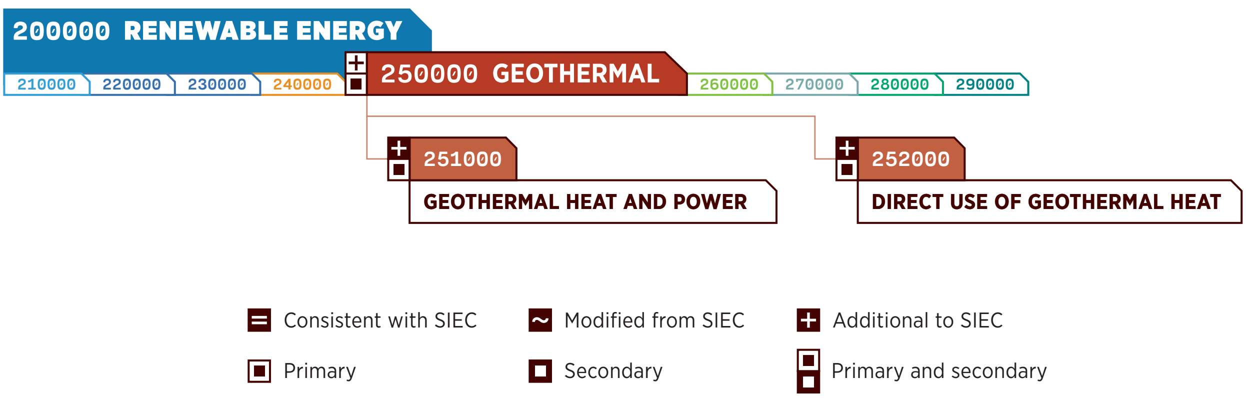
Other solar thermal energy not elsewhere specified, such as the use of solar cook stoves.

250000 GEOTHERMAL ENERGY

Geothermal energy refers to heat extracted from the ground, usually in the form of hot water or steam and typically referred to as hydrothermal fluid. The sources of this heat include radioactive decay in the Earth's crust and mantle and heat transferred from the core of the Earth to the crust. The hot water or steam used in geothermal energy production may come from natural sources (groundwater, underground aquifers, rivers or springs), or it may be injected into the ground (with or without pumping). The main division in geothermal energy stems from the purpose for which the energy is intended: to produce electricity for the grid (and commercial heat), in which case it is categorised as geothermal heat and power (251000), or to produce heat for direct consumption across energy subsectors, in which case it is categorised as direct use of geothermal heat (252000).

Geothermal energy has similarities with ground-source heat pumps (293000). Typically, if the geothermal energy is extracted from depths greater than 100 m and accesses natural geothermal reservoirs of steam or water, then it would be considered geothermal energy. If the system extracts thermal energy from shallow depths of less than 100 m and the energy is not used for electricity generation, or the system does not access geothermal reservoirs, it would be categorised as ground-source heat pumps.

Figure 13 IRENA classification of geothermal energy



251000 Geothermal heat and power

Geothermal heat and power involves electricity generation from geothermal heat in thermal power plants and direct heat use. It excludes energy from ground-source heat pumps and other sources used to improve geothermal heat quality. Geothermal energy provides a constant source of power, making it suitable for baseload power production.

Statistics for geothermal energy cover heat production, electricity generation and capacity. The primary energy used for electricity generation is the energy content of the steam, or ten times the amount of electricity produced if the energy content of the steam is not measured. For commercial heat production, a 50% conversion efficiency is assumed if direct measurements are unavailable.

Geothermal power plants include dry steam plants, flash steam plants and binary steam plants. Dry steam plants use steam directly from the ground, while flash steam plants use hydrothermal fluids above 182°C. Binary steam plants use hydrothermal fluids between 107°C and 182°C and exchange heat with a working fluid in a closed loop. Combined or hybrid plants use at least two of these three methods. Combined heat and power plants produce electricity and heat (as hot water) usually for district heating (IGA, 2018). When this is the case, the energy used for district heating should be included in the direct use of geothermal heat category (252000).

252000 Direct use of geothermal heat

Direct use of geothermal heat refers to the heat generated by geothermal heat exchangers mainly used for space heating and cooling (IGA, 2018).

Geothermal energy has diverse uses, including in agriculture and manufacturing. Its direct applications, like food processing and fabric drying, require lower temperatures than electricity generation, making such direct applications promising areas for development (IGA, 2018).

Direct use of geothermal heat also includes district heating, which is a thermodynamical system that provides heating to multiple buildings or an entire community using geothermal energy as the primary heat source. A centralised geothermal power plant supplies heat to a network of pipes that distribute hot water or steam to multiple buildings. The buildings then use heat exchangers to extract the heat from the hot water or steam for space heating, domestic hot water and other applications. After cooling, the water returns to the geothermal plant to be reheated and reused within the network.

Several countries have implemented geothermal district heating systems, including China (Hardarson, 2021), France (Richter, 2020), Iceland (Iceland Renewable Energy Cluster, 2021) and Türkiye (Mertoglu, 2001).

Geothermal district heating systems:

- are large-scale systems that supply heat to multiple buildings
- are designed specifically for space and domestic hot water heating
- centralise a heat source with a network of pipes and heat exchangers in each connected building.

260000 BIOENERGY

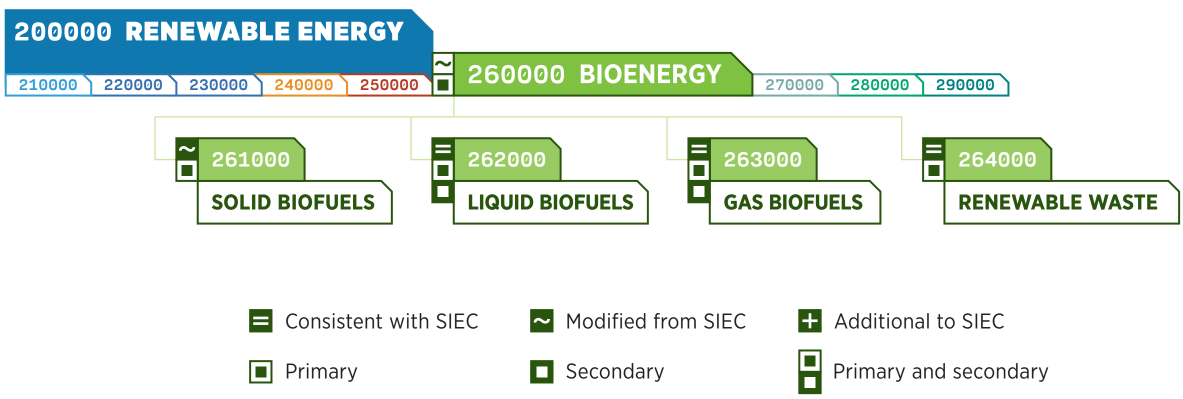
Bioenergy is the energy derived from biological compounds (trees, crops) that are renewable due to their short life cycle within the carbon dioxide cycle.[9] Bioenergy encompasses the direct use (consumption) of these compounds for heat production, as well as their use for electricity and commercial heat production. It also includes the compounds' transformation from one state (solid, liquid or gas) to another and their transformation into secondary products (*e.g.* biomethane or biomass pellets). Bioenergy is classified into four categories: solid biofuels, liquid biofuels, gas biofuels and renewable waste. The first three are based on the physical state of the biofuel, and the last one reflects the post-consumption condition of biological matter, regardless of its physical state.

Solid biofuels include all solid non-fossil materials of biological origin used solely for energy purposes; liquid biofuels comprise liquids derived from biomass that are used as fuels, such as alcohols, fatty acid esters, synthetic hydrocarbons and vegetable oils. Gas biofuels are gases produced through thermal processes or through anaerobic digestion of organic matter like livestock manure, cooking residues, agricultural residues, and wastewater sludge. Renewable waste includes by-products of human activities, further categorised into municipal or industrial renewable waste.

⚠ Bioenergy excludes mechanical energy derived from biological entities, such as the use of animals for motion in forestry and agriculture. It also excludes the non-energy uses of biological compounds and the use of food crops as bioenergy feedstocks. Thus, sugar is not considered a type of solid biofuel, but bioethanol fuel produced from sugar is counted as a liquid biofuel.

In energy statistics, bioenergy includes all electricity generated from the use of biofuels in thermal power plants, plus the (commercial) heat produced from the burning of biofuels in combined heat and power plants or heat production plants. It also includes the use of biofuels as transport fuels and the direct use of biofuels to produce heat or as energy sources in industrial processes, such as in cement production.

Figure 14 IRENA classification of bioenergy



[9] *If biomass is being used faster than it is being replaced, this would normally be referred to as an unsustainable level of production rather than as non-renewable production.*

Bioenergy includes both primary and secondary (processed) biofuels. While charcoal is the main secondary biofuel considered in national energy statistics and IRES, in this taxonomy IRENA proposes several secondary products including pellets and briquettes. Some liquid biofuels and biogases may also be recorded as secondary products.

When biofuels are used to produce electricity or heat, this should be recorded as a transformation energy flow (*i.e.* there is an input of bioenergy and an output of electricity and/or heat). This information is often recorded in power plants, and assumptions or estimations should only be used when there is no operational data.

261000 Solid biofuels

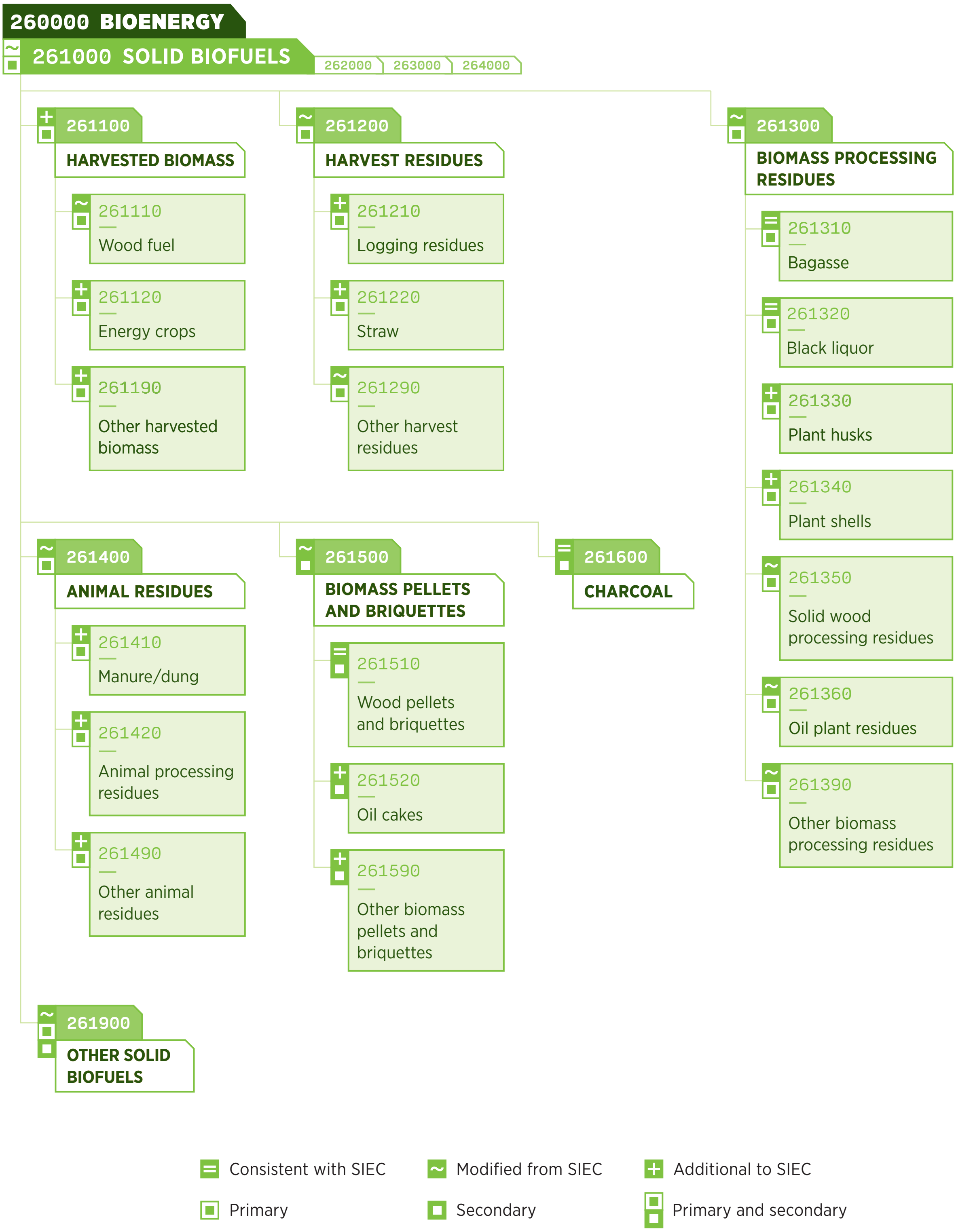
Solid biofuels are any solid non-fossil materials of biological origin used solely for energy purposes, including products grown for such purposes and a wide range of residues of biological origin. Solid biofuels are also known as "biomass" and include crops and animal products in the form of solids. Solid biofuels also include secondary energy carriers, like charcoal and biomass pellets and briquettes. The IRENA classification of biofuels groups them as primary or secondary products – with the primary products also divided by source – as follows:

- **Primary solid biofuels**
  - Harvested biomass: wood fuel, energy crops, and other harvested biomass
  - Harvest residues: logging residues, straw, and other harvested biomass
  - Biomass processing residues: bagasse, black liquor, plant husks, plant shells, solid wood processing residues, oil plant residues, and other biomass processing residues.
  - Animal residues: manure/dung, animal processing residues, and other animal residues.
- **Secondary solid biofuels**
  - Biomass pellets and briquettes: wood pellets and briquettes, oil cakes, and other biomass pellets and briquettes.
  - Charcoal
- **Other solid biofuels**

Splitting primary solid biofuels by source reflects interest in the environmental impacts of the different ways biological resources enter the bioenergy production chain.

⚠ In energy statistics, solid biofuels should be reported in tonnes, and the energy content should be reported in joules based on measured net calorific values.

Figure 15 IRENA classification of solid biofuels.



Biomass pellets and briquettes, as well as charcoal, can be produced with any primary solid biofuel. The sum of all primary and secondary solid biofuels yields the total solid biofuels. When considering secondary products in the energy balance, transformation processes must be accounted for to avoid double counting or the mixing of higher energy content products with lower-energy unprocessed products.

As solid biofuels are significantly important in the energy system, and because they are vast in their variety, starting from vegetal or animal sources, this taxonomy uses a combined approach to divide the solid biofuels category into its components. Harvested biomass (261100) refers to biomass harvested for energy purposes. Harvest residues (261200) are energy products left from harvesting activities for non-energy purposes. Biomass processing residues (261300) include those residues from biomass processing activities across different economic or energy sectors that use solid biofuels as raw materials. Unlike the previous categories, which are based on vegetal sources, the animal residues category (261400) encompasses the solid biofuels sourced from animal matter. Biomass pellets and briquettes (261500) and charcoal (261600) are secondary energy products that can be produced from one or more biofuels after undergoing physical and/or chemical transformations.

+ 261100 Harvested biomass

Harvested biomass is an aggregate group that includes wood fuel, energy crops and other harvested biomass. Harvested biomass can be used directly or as a feedstock for various bioenergy applications, including combustion for heat and power generation, compression to make biomass pellets and briquettes, and gasification for liquid and gas biofuel production. Harvested biomass is divided by the type of crop being harvested.

~ 261110 Wood fuel

Wood fuel refers to the woody biomass derived from trees, when harvested specifically for energy use (see Box 1). It includes wood from the main stem, branches, and other parts of trees (*e.g.* tops, small branches and twigs, stumps, roots, and bark) so long as they are harvested specifically for fuel. It excludes those other parts of trees if they are produced only as a by-product of logging operations (logging residues) and also excludes trees grown in short-rotation management systems (energy crops). Wood fuel can be removed from the forest in solid form as logs, sticks or bundles of sticks or can be chipped in the forest and removed as wood chips.

Wood fuel is primarily used for heating and cooking in residential, commercial and industrial settings, as well as for electricity and heat generation in biomass-fuelled power plants (FAO, 2009).

+ 261120 Energy crops

Energy crops are other woody or herbaceous plants grown specifically for biofuel production. This category includes trees grown on short rotations (*e.g.* short-rotation coppice); grasses like miscanthus, switch-grass, and elephant grass; vines like kudzu; and other herbaceous plants (AFWA, 2012). It excludes food crops grown as feedstocks for liquid biofuel production (*e.g.* maize, sugar cane or oil palm) and crops grown for anaerobic digestion.

Energy crops typically are densely planted, are intensively managed and have high yields of cellulose with frequent harvests. These crops are primarily burned directly for heat, electricity and commercial heat production. However, they can also be transformed into secondary fuels like biomass pellets and briquettes or liquid and gas biofuels. When data are available, the amounts of energy crops used to produce secondary fuels should be recorded as primary energy sources.

Box 1 Correspondence with Food and Agriculture Organization of the United Nations (FAO) Classification of Forest Products 2022

The FAO Classification of Forest Products (FAO, 2022) contains many categories of wood products relevant to the collection of solid biofuel data. The classification is largely based on the observable physical characteristics of forest products, such as the source of the wood (part of the tree), the species (coniferous, non-coniferous, other), the degree of processing of the product, the processing technology used and the intended use. The intended use includes use for energy, but this is the lowest level of the classification, resulting in many FAO product codes falling into each category defined in the IRENA taxonomy. The correspondence between the FAO classification and the IRENA taxonomy is shown in the table below.

IRENA taxonomy	FAO classification
Wood fuel — (261110)	011.1 Wood fuel from the main stem and branches 011.9 Other wood fuel (part) 032.114 Wood chips and particles from wood in the rough, coniferous, for energy 032.194 Other wood chips and particles from wood in the rough, for energy
Logging residues — (261210)	011.9 Other wood fuel (part)
Solid wood processing residues — (261350)	031.114 Solid wood processing residues, coniferous, for energy 031.194 Other solid wood processing residues, for energy 031.214 Sawdust, coniferous, for energy 031.294 Other sawdust, for energy 031.314 Shavings, coniferous, for energy 031.394 Other shavings, for energy 031.492 Other bark removed during processing, for energ 031.911 Other residues of wood processing, not of solid wood, coniferous, for energy 031.991 Other residues of wood processing, not of solid wood n.e.c., for energy 032.214 Wood chips and particles from wood processing, coniferous, for energy 032.294 Other wood chips and particles from wood processing, for energy
Wood pellets and briquettes — (261510)	041.11 Wood pellets, coniferous, for energy 041.91 Other wood pellets, for energy 042 Wood briquettes 043.11 Other agglomerates, coniferous, for energy 043.91 Other agglomerates n.e.c., for energy
Charcoal — (261600)	021.11 Wood charcoal, coniferous, for energy 021.91 Other wood charcoal, for energy 022.11 Torrefied wood, coniferous, for energy 022.91 Other torrefied wood, for energy
Other solid biofuels — (261900) Renewable municipal waste — (264100) Renewable industrial waste — (264200)	032.314 Wood chips and particles from recovered wood products, coniferous, for energy 032.394 Other wood chips and particles from recovered wood products, for energy 033.114 Uncontaminated recoverable wood products, coniferous, for energy 033.194 Other uncontaminated recoverable wood products, for energy 033.211 Contaminated recoverable wood products, coniferous, for energy 033.291 Other contaminated recoverable wood products, for energy

Note: n.e.c. = not elsewhere catergorised.

Most of the FAO codes fall within just one of the IRENA categories; two notable exceptions may fall within more than category:

- FAO defines "other wood fuel" as "wood from other parts [of trees] than main stem and branches where these are harvested for fuel", but it does not distinguish between wood harvested specifically for energy production (*e.g.* collecting dead wood for wood fuel) and wood fuel that arises as a by-product of other forest harvesting activities. In the IRENA taxonomy, the former would be counted as wood fuel, and the latter would be counted as logging residues.
- FAO has several codes for the production of energy from recovered or recoverable wood products. This is post-consumer wood waste that has been sorted and will be used for energy purposes. In this case, the FAO classification is clear, but its translation into energy statistics is not so clear. If detailed data are not available, recovered wood products should be captured as part of the two IRENA codes for renewable waste. However, if detailed data are available, IRENA recommends recording these products as other solid biofuels and excluding them from renewable waste statistics. The main purpose of highlighting this product type is to ensure that it is included somewhere in bioenergy statistics, without double-counting.

Two other points should be considered when working with the FAO classification and the IRENA taxonomy:

- FAO does not clarify what the term "for energy" includes. IRENA would define this as including all uses of wood for energy (*i.e.* direct use, heat and power production, and as a feedstock for the production of secondary biofuels).
- FAO treats wood chips as a partly processed product manufactured outside a forest. Thus, wood chips for energy made on site in a forest are classified as wood fuel, but if wood is chipped off-site then those products are classified as wood chips. Wood chips for energy from wood processing by-products or from waste (recovered wood products) have a well-defined source, but if they are made off-site from roundwood (wood in the rough) then it is not clear where they should be recorded. Roundwood removed from a forest only for energy use and chipped off-site should be counted as part of wood fuel, but roundwood may also be taken for chipping off-site for another use or unspecified purpose. This would not be classified as wood fuel when it leaves the forest, but some wood chips made from that wood may be used for energy and should also be counted as part of wood fuel. These products are given the codes 032.114 and 032.194 by FAO and are likely to mostly capture the output of wood chipping plants that has not met the quality requirements for processing into pulp or wood panels.

261190 Other harvested biomass

Other harvested biomass refers to non-wood plant materials taken from the land that have not been planted or managed specifically for energy use but have been harvested for this use. It includes plant materials like bamboo, reed canary grass (Kukk *et al.*, 2011) and invasive weeds with potential energy crop applications.

These types of biomass can be used similarly to wood fuel and energy crops: they can be burned for heat or electricity or converted into secondary fuels or other biofuel types. Their use is especially important in regions with scarce wood fuel resources or where wood fuel use is not environmentally sustainable.

261200 Harvest residues

Harvest residues are the materials left on cultivated land after harvesting crops or after forestry operations. The harvest residues category is divided by the type of crop group left over after the harvesting or forestry operations. The subcategories are logging residues (*e.g.* bark, branches) as well as straw and other harvest residues when used for energy purposes.

Harvest residues can be used to produce liquid biofuels, such as cellulosic ethanol, which can be blended with gasoline to fuel vehicles. Harvest residues can also be burned directly to produce heat and electricity in biomass-fired power plants (Schipfer *et al.*, 2022).

261210 Logging residues

Logging residues refer to the by-products left in the forest after logging operations. They consist of woody debris from final felling, such as stems, branches, roots, stumps, bark, needles, leaves and twigs, as well as small trees from thinning and clearing operations with unsaleable stem wood. Logging residues can be removed from the forest whole or in bundles but are frequently chipped. Wood chips produced from logging residues are included in this category, but wood chips produced from trees purposely harvested for wood fuel production are excluded (and would be classified as wood fuel [261110]).

Logging residues can be used as a source of heating or electricity generation, as well as for producing other biofuels.

261220 Straw

Straw refers to the dry stalks and other residues of cereal plants (*e.g. barley, corn and wheat*) that remain after the edible parts of the plant have been removed. All residues of cereal plants left in fields after harvesting should be included in the straw category. This includes the stalks, husks and maize cobs.

Straw is a primary energy source that can be used to generate electricity and produce heat for sale or direct use. It can also be converted into secondary biofuels such as biomass pellets and briquettes or transformed into other types of biofuel.

⚠ The energy derived from straw does not include the energy produced when the straw is burned for waste disposal or to return nutrients to the soil, nor the energy produced from cereal residues during later stages of processing, which would be classified as plant husks (261330) or other biomass processing residues (261390).

Straw typically accounts for half or more of the total biomass yield of most cereal crops. If straw is used as a source of energy, it is usually collected and tied into a bundle (bale) for storage and transportation, or it may be converted into biomass pellets. The most common use of straw for energy currently is to produce heat used in agriculture (direct use).

261290 Other harvest residues

Other harvest residues are any residues left over after harvesting crops, excluding straw and logging residues. These residues can include leaves, stems, roots and other non-edible parts of crops, as well as other agricultural residues.

261300 Biomass processing residues

The biomass processing residues category is an aggregate of the by-products obtained during the processing of different types of biomass, such as roundwood or agricultural crops, that have significant energy potential. Many of these residues have non-energy uses (*e.g.* as feed, mulch or animal bedding or for the production of reconstituted wood panels), so only the share of these residues used for energy should be counted in energy statistics.

These residues include bagasse, black liquor, plant husks, plant shells, solid wood processing residues, oil plant residues and other biomass processing residues. Since these residues are already collected during the processing of biomass, they can be a convenient and inexpensive source of biomass for energy production. These residues can be used for direct combustion or gasification, or they can be further processed into advanced biofuels, such as bio-oil or biogas (Bioenergy Insight, n.d.).

261310 Bagasse

Bagasse is a fibrous residue material generated during the production of sugar from sugarcane, sorghum or agave. Fresh bagasse typically contains cellulose, hemicellulose, lignin and other chemicals, with a moisture content of about 40-50% by weight. Bagasse is mainly used for heat or combined heat and power generation in sugarcane processing facilities, including ethanol production plants. Bagasse can also serve as a primary fuel to be converted into secondary fuels such as biomass pellets and briquettes. The energy from bagasse excludes the energy extracted from the original plants in the form of sugar and the energy produced from the residues of other plants used to make sugar.

Wet bagasse production accounts for approximately 30% of the weight of sugarcane processed in a sugar mill, which is typically sufficient to meet the heat and power requirements of sugar processing. Many large sugar mills generate surplus electricity from bagasse and sell it to the grid. However, since bagasse production is seasonal, some sugar mills may run their power plants on other fuels during periods when sugar is not being produced. In such cases, the heat and power produced from bagasse should be based on its share of the total energy content of all fuels used in heat and power production.

⚠ In some tropical regions, bagasse production can be year-round, thus becoming a more significant source of baseload power for the grid.

261320 Black liquor

Black liquor is a by-product of the kraft pulping process used in paper production (UNSD, 2018). Black liquor is composed of organic chemicals from wood, as well as inorganic chemicals used in the pulping process. Its main use is as a fuel, and it is classified as a solid biofuel because the organic compounds in the solution are used for energy production and the inorganic chemicals can be recycled into the pulping process. It is a primary source of energy used for electricity generation and heat production, with the possibility of producing other biofuels.

Black liquor is an aqueous solution with a high concentration of solids. The organic chemicals in black liquor are typically 40-45% soaps, 35-45% lignin and 10-15% other organic chemicals (Moses *et al.*, 2022). The inorganic component is mostly soluble salt ions (Cardoso *et al.*, 2009). Black liquor retains over 50% of the wood's energy content used in pulping, making it an efficient source of energy. Recovery boilers are used to increase the concentration of solids in black liquor through multiple evaporation processes, with modern boilers achieving concentrations of up to 85%.

The combustion of black liquor solids in recovery boilers produces high-pressure steam that generates electricity and provides heat for the pulping process. Other technologies, such as black liquor gasification, are being explored for more efficient energy production. Additionally, products such as tall oil, turpentine and other resins can be separated from the solution during the evaporation process and used for non-energy purposes, converted into biogases or liquid biofuels, or used for electricity and heat production.

261330 Plant husks

Plant husks (or hulls) are the protective coatings of seeds or grains of various plants, such as rice, which protect the seed during its growing season. The husks are formed from hard materials such as silica and lignin. Plant husks may be removed from grains manually, but they are now mostly removed in mills, making mills the main producers of energy from plant husks.

Plant husks are a primary energy source used to generate electricity and produce heat for sale or direct use. They may also be converted into secondary fuels (biomass pellets and briquettes) or transformed into other types of biofuel.

The most common type of energy derived from plant husks is electricity or combined heat and power. This is produced from the plant husk residue in mills and is used to power the milling machines. Plant husks are not a significant source of bioenergy at the global level, but they are important in some countries and can be used to produce power (or combined heat and power) at a relatively small scale, especially in modern power plants that use gasification technologies. Another emerging trend is the production of plant husk pellets that can be transported to existing thermal power plants for co-firing with other types of fuel.

261340 Plant shells

Plant shells are the outer coverings of nuts and seeds, such as coconut shells, palm kernel shells and almond shells. They are typically hard, woody and fibrous in texture. Plant shells can be burned and used as a fuel for heat and electricity generation.

261350 Solid wood processing residues

Solid wood processing residues are by-products from lumber, plywood, particleboard and other wood product manufacturing. They include materials such as sawmill rejects, slabs, edgings and trimmings, veneer log cores, veneer rejects, sawdust, and residues from carpentry and joinery production (Eurostat *et al.*, 2021). They also include wood chips made from these residues (see Box 1). This category only includes the share of these residues used for energy production and excludes any amounts used for other purposes. These materials are typically collected and repurposed for heat or electricity generation or as feedstocks for biomass pellet production.

261360 Oil plant residues

Oil plant residues are the residues left over after the extraction of oil from crops such as olives, sunflower, soybean, rapeseed and palm fruit. The residues are typically high in fats and can be used as a feedstock for biodiesel production or as a source of thermal energy through combustion. This category only includes the share of these residues used for energy production and excludes any amounts used for other purposes.

When compressed into cakes, these residues undergo a transformation process, producing oil cakes (261520), and should be recorded within the transformation block of an energy balance.

261390 Other biomass processing residues

Other biomass processing residues include by-products from processing other types of biomass that are used for energy but are not covered by the other specific categories. Such residues include those from the processing of non-woody biomass, such as fruit processing residues (*e.g.* apple pomace), or those from food processing operations not included in other categories.

261400 Animal residues

Animal residues refers to the excreta of animals, as well as the residues from meat and fish, that can be used directly as a fuel when dry. The two main categories of animal residue stem from whether the residue is a continued waste product of animals or the actual animal parts themselves. Examples of animal residues include cow dung, poultry litter and fish body parts. These residues can be burned to generate heat and electricity or used as fuel for cooking and heating in households. Animal residues used in anaerobic fermentation plants are excluded from this category; they are included under animal residues biogas (263130).

261410 Manure/dung

Manure/dung is animal excrement that can be used as a source of energy. It is often used as fuel for heating and cooking in rural areas in numerous countries. Dung is typically collected from livestock, such as cattle, horses and pigs, as well as from poultry, and is often mixed with other organic residue materials, such as straw and crop residues, to improve its energy content and handling characteristics.

261420 Animal processing residues

Animal processing residues are the by-products from the slaughter and processing of animals. The use of animal processing residues for energy production can provide economic and environmental benefits by reducing waste disposal costs and providing a source of renewable energy. However, their use must comply with regulations regarding waste disposal and public health.

261490 Other animal residues

Other animal residues are any animal residues not covered under the manure/dung or animal processing residues categories. These residues might include feathers, hair, bones or other animal by-products. These residues may have energy potential and, if so, could be burned as a fuel.

261500 Biomass pellets and briquettes

Biomass pellets and briquettes are solid and processed biofuels made from dried, cut/crushed and compressed biomass. Wood pellets, created from fuelwood or wood residues, are the most common, but other solid biomass materials such as rice husks, straw, nut shells and renewable municipal waste can also be used. The subdivisions in this group are based on the biomass source used to produce the pellet or briquette, and the quantity of divisions is based on the significance of each energy source. Producing these biofuels involves compressing the biomass or adding a binder, which typically makes up less than 3% of the final weight. These biofuels have low moisture content (below 10%) and high combustion efficiency. Pellets are cylindrical with diameters under 25 mm and lengths under 100 mm; briquettes are also cylindrical but can vary in size.

Biomass pellets and briquettes are primarily used for heat production (either sold or for direct use) and are increasingly used for electricity generation in countries that rely on imported biofuels to meet bioenergy targets.

⚠ Torrefied biomass pellets and briquettes, known as black pellets or bio-coal, are not included in this category and should be classified as charcoal (261600).

When reporting biomass pellet and briquette use, data on the primary energy sources (solid biofuels) used for production should be included in their respective categories, with the amounts used for manufacturing indicated as other transformation in the energy balance. If available, the renewable content of pellets and briquettes made from refuse-derived fuel and solid recovered fuel can also be included, with the primary input amounts appearing in the statistics for renewable municipal waste (264100).

261510 Wood pellets and briquettes

Wood pellets and briquettes are compressed forms of wood biomass, typically made from sawdust, shavings and other wood processing residues, and are often burned for heat and electricity generation.

Both wood pellets and briquettes have a higher energy density than traditional firewood and produce less smoke and ash when burned, making them a more efficient and environmentally friendly fuel source (FAO, 2022).

261520 Oil cakes

Oil cakes are the compressed solid residues remaining after the oils are removed from seeds and other agricultural products, resulting in oil plant residues (261360), which are then compressed into cakes. Oil cakes are typically used as animal feed, but when used for energy purposes, they should be considered in this category.

The main difference between oil plant residues (261360) and oil cakes (261520) is that oil cakes are further processed by physical compression or filtering and/or chemical transformations to remove toxins and pollutants, thus increasing their net calorific value.

261590 Other biomass pellets and briquettes

The other biomass pellets and briquettes category refers to pellets and briquettes made from sources other than wood and oil seeds, such as agricultural residues, energy crops and renewable industrial waste. Examples of other biomass materials used for pellets and briquettes include straw, corn cobs, peanut shells, sunflower and rice husks, and bagasse. These materials are compressed into dense, compact forms that can be used as a source of energy in various applications, including heating, cooking and electricity generation (FAO, 2022).

261600 Charcoal

Charcoal is a secondary solid biofuel obtained through the carbonisation of wood or other vegetable matter in an oxygen-free environment. It mainly consists of carbon, with small amounts of ash and other impurities. Charcoal is typically made from wood (fuelwood and wood residues) but can be made from almost any type of solid biomass.

Carbonisation usually involves slow pyrolysis, where biomass is heated in a controlled environment without air for several days (for artisanal charcoal). Alternatively, charcoal can be produced more quickly in an industrial kiln or retort that operates at high temperatures. Heat for the charcoal-making process can come from partial combustion of the original biomass or other energy sources.

Charcoal is primarily used for direct heat, with cooking and iron and steel production being the most common uses, where it substitutes for coke. It also has non-energy uses, such as in medicine and filters as activated carbon. Charcoal comes in various forms, depending on the type of primary solid biofuel used, including lump charcoal from fuelwood, charcoal briquettes, bamboo charcoal and charcoal made from compressed wood pellets and briquettes.

Additionally, torrefied biomass pellets and briquettes are classified as charcoal and can be used as a substitute for coal and for co-firing in thermal power plants (Nunes *et al.*, 2014). Torrefied biomass is different from charcoal produced through the traditional slow pyrolysis process, since it involves heating the biomass at lower temperatures and for shorter periods of time.

261900 Other solid biofuels

Other solid biofuels includes all solid non-fossil materials of biological origin used for energy that are not counted elsewhere. Where detailed statistics about the use of recovered wood products for energy are available, these amounts can be counted in this category if they are not included in renewable waste (264000).

262000 Liquid biofuels

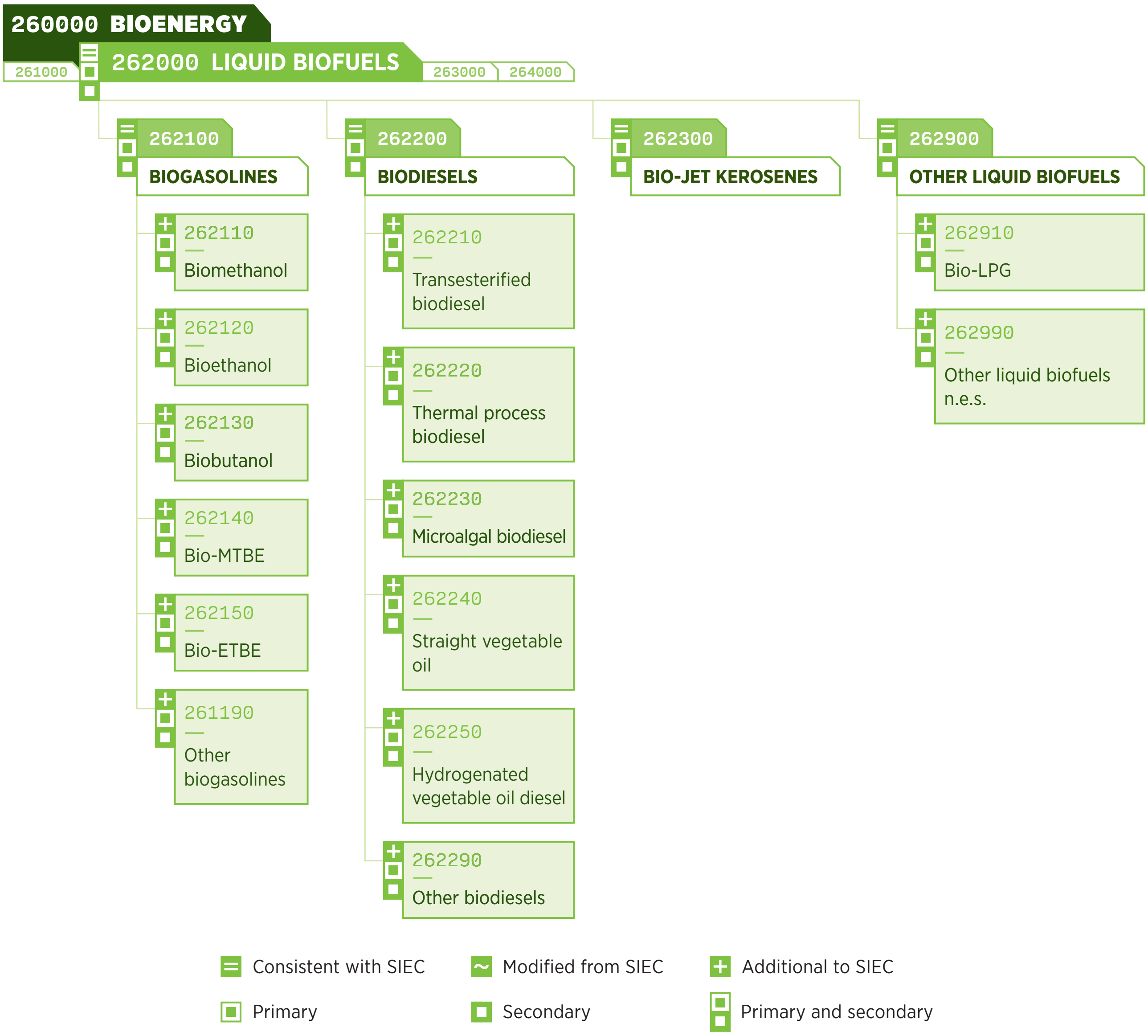
Liquid biofuels are liquids obtained from biomass and used as fuels. They include various alcohols, fatty acid methyl (or ethyl) esters, synthetic hydrocarbons and vegetable oils used directly as fuel. This category comprises biogasoline, biodiesel, bio-jet kerosene and other liquid biofuels. The division into these groups is based on the biofuel's suitability to blend with similar fossil fuels.

Liquid biofuels are mainly used as transport fuels but can also be used for electricity generation (*e.g.* in diesel generators) or for heating. They are often blended with liquid fossil fuels such as petroleum gasoline and diesel. In these cases, only the biofuel component should be counted as renewable energy.

⚠ Liquid biofuels and gas biofuels are **primary** if the biomass feedstock used to produce them is not part of the energy system and is thus out of the scope of energy statistics (*e.g.* non-energy crops, waste products or new energy pathways). They are **secondary** if the biomass feedstock used to produce them is an energy product or biomass that would otherwise be used for energy purposes (*e.g.* energy crops or wood fuel).

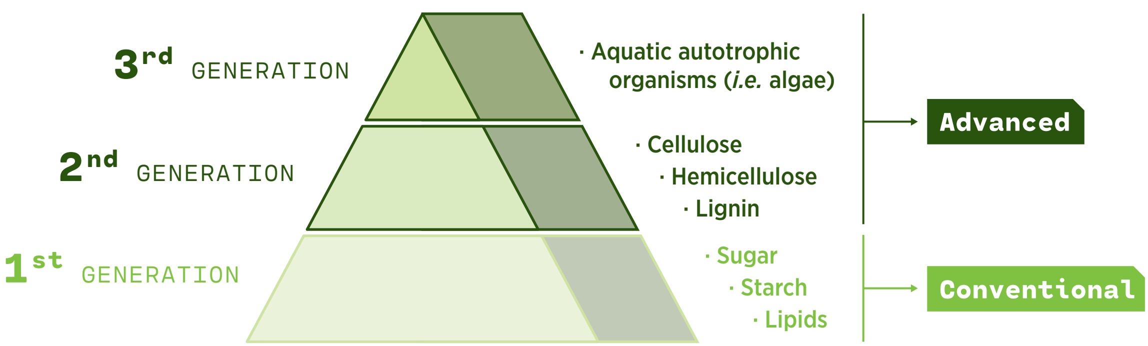
Liquid biofuels can be either primary or secondary products. National energy statistics and IRES typically treat all liquid biofuels as primary energy products, without recording the energy content of the solid materials used to produce these fuels. Liquid and gas biofuels can be produced from biomass feedstocks that are within or outside the energy system. And this distinction should determine whether these energy products are primary or secondary. When secondary, energy statistics should include the biomass feedstock as a primary energy product, and then record the transformation of the feedstock into the specific liquid or gas biofuel in question.

Figure 16 IRENA classification of liquid biofuels



Notes: ETBE = ethyl tertiary-butyl ether; LPG = liquefied petroleum gas; MTBE = methyl tert-butyl ether; n.e.s. = not elsewhere specified.

Figure 17 Traditional generational classifications of biofuels



Based on: ETIP Bioenergy, 2016.

262100 Biogasolines

Biogasolines refer to liquid fuels derived from biomass that could be used in spark-ignition internal combustion engines. This category includes biomethanol, bioethanol (both hydrous and anhydrous), biobutanol, bio-MTBE (methyltertio-butyl-ether) and bio-ETBE (ethyl-tertio-butyl-ether). Each division is based on the chemical composition of the products, irrespective of their use, energy sources or production methods. Bioethanol, bio-ETBE and biobutanol are the most common types of biogasoline.

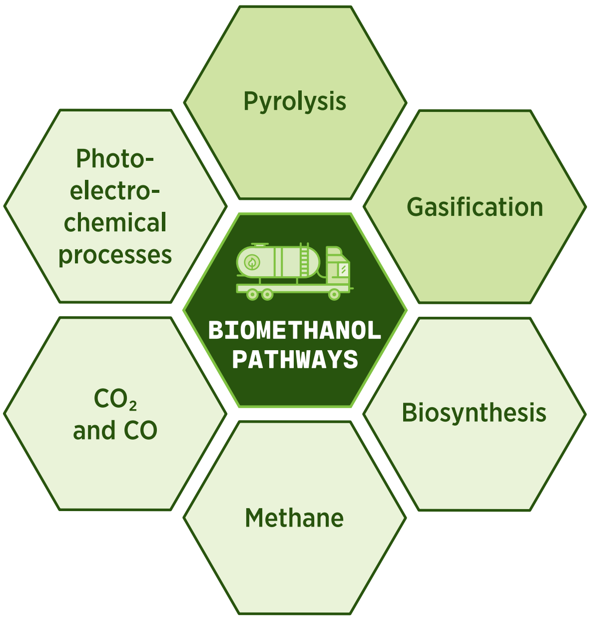
Biogasolines can be blended with petroleum gasolines or used directly in engines. Blending may occur in refineries or at or near the point of sale.

In energy statistics, biogasolines are usually considered primary energy products, with any solid biofuels and renewable waste used in their production not being recorded. However, advanced biogasoline should be recorded as a secondary energy product if data are available, since its feedstocks often come from primary biofuels. When accounting for transformation flows into biogasoline, energy statisticians should consider transformation losses.

262110 Biomethanol

Biomethanol is a one-carbon alcohol (CH_3OH) that is chemically identical to fossil-based methanol. However, the prefix “bio” is used to differentiate it from methanol produced from fossil fuels. Biomethanol is produced from organic matter using different synthesis pathways, most commonly pyrolysis or gasification (Luque *et al.*, 2023).

Figure 18 Pathways to produce biomethanol



Based on: Shamsul *et al.*, 2014.
Notes: CO = carbon monoxide; CO_2 = carbon dioxide.

Biomethanol can be produced from many renewable feedstocks, including agricultural residues, forest residues, animal residues, wastewater and energy crops (Shamsul *et al.*, 2014). First, the feedstock is converted into gas biofuel, which is then transformed into biomethanol using different synthesis pathways. Biomethanol has equivalent properties to fossil fuel-based methanol and can be used for the same applications. Moreover, it could be blended with gasoline for internal combustion engines (IRENA, 2016).

262120 Bioethanol

Bioethanol is a two-carbon alcohol (C_2H_5OH or CH_3CH_2OH) that can be used in spark-ignition internal combustion engines, serving as a biogasoline. It can be blended with petroleum gasoline in different ratios, ranging from E5 (5% bioethanol and 95% gasoline) to E100 (100% bioethanol). At high concentrations, it is corrosive to conventional engines. The two traditional types of bioethanol are typically referred to as conventional and advanced biogasoline and span three generations[10] of bioethanol depending on the feedstock used (see Figure 17).

Conventional biogasoline (1st generation bioethanol)

- **Fermented ethanol** is also known as first-generation bioethanol or traditional biogasoline; the feedstock is edible crops such as corn, sugarcane or wheat. Ethanol is produced from anaerobic digestion of biomass, then it is distilled, dehydrated and eventually denatured. An important consideration in its production is that the use of edible crops can lead to competition for food resources and land use (Bertrand *et al.*, 2016).

Advanced biogasoline (2nd and 3rd generation bioethanol)

- **Thermochemical cellulosic ethanol**, also known as second-generation bioethanol or advanced biogasoline, uses non-edible crops like crop residues, forestry residues, energy crops and sorted municipal waste as feedstock. These cellulosic materials, containing cellulose and hemicellulose, require an additional step to break down the long chains of sugars before they can be converted into liquid biofuels. The biomass undergoes a thermochemical process like pyrolysis or gasification to produce liquors from the distillation (Brown, 2015). Afterwards, ethanol is purified from the distillate.

- **Fermented algal ethanol**, also known as third-generation bioethanol or advanced biogasoline, is a biofuel derived from algae as its primary feedstock. The production process for fermented algal ethanol involves several stages, starting with the hydrolysis of algae to break down complex carbohydrates into simple sugars. The sugars are then fermented using micro-organisms such as yeast, which convert them into ethanol (Maity and Mallick, 2022). The final step is distillation, where the ethanol is separated from the fermentation broth and purified. Algae can be grown in various environments, including brackish water and wastewater, and do not compete with food crops for land use. Additionally, algae can be grown on non-arable land, making this process a sustainable option for biofuel production (Jambo *et al.*, 2016).

[10] *We refer to the traditional generations of biogasoline in this document, although we do not highlight them as separate categories of bioethanol, given that the chemical compound remains largely the same. As such, the differences between the feedstocks should be accounted for in energy balances as transformation processes, rather than pointing out different energy products for the bioethanol. The traditional generations of biodiesels have been categorised separately, however, because the chemical compounds of biodiesels of each traditional generation can be significantly different.*

While conventional biogasoline is a primary energy product because its feedstocks are not part of the energy system, advanced biogasoline is often considered a secondary energy product that is used as a transport fuel. Advanced biogasoline may be blended with petroleum gasoline or used directly in engines. When blended, in energy statistics, the energy from advanced biogasoline only accounts for its contribution to the total energy content of the blended product, excluding the energy from other types of fuel in the product. If adequate data are available, the amount of solid biofuels and renewable waste used as primary energy in the manufacturing of advanced biogasoline should be recorded. This would appear as a flow to transformation (for each solid biofuel used) and a flow from transformation (excluding transformation losses) for advanced biogasoline. Where data are inadequate, advanced biogasoline can be treated as a primary energy product with no transformation.

⊞ 262130 Biobutanol

Biobutanol is a four-carbon alcohol (C_4H_9OH or $CH_3CH_2CH_2CH_2OH$) produced from starch via the acetone-butanol-ethanol fermentation pathway (Koutinas *et al.*, 2016). Biobutanol can be used as gasoline in internal combustion engines, serving as a biogasoline. It is chemically identical to the butanol produced from fossil fuels. Among its benefits compared with other biofuels, biobutanol is less hygroscopic, corrosive and volatile (Dürre, 2007), making it easier to store, mix with gasoline at refineries, and transport.

⊞ 262140 Bio-MTBE

Bio-MTBE (methyl tert-butyl ether) is a chemical compound [$C_5H_{12}O$, or $(CH_3)_3COCH_3$] derived from biomethanol. As a biofuel additive, bio-MTBE can be blended with gasoline to enhance its properties, such as increasing its octane number and reducing its environmental impact (Grippi *et al.*, 2020).

Fossil MTBE has been used as a gasoline additive to increase octane rating and reduce engine knocking. However, due to concerns about its potential to contaminate groundwater and its health risks, the use of fossil MTBE has been phased out in many countries, including the United States and the European Union countries (Krayer von Krauss and Harremoës, 2002).

⊞ 262150 Bio-ETBE

Bio-ETBE (ethyl tertiary-butyl ether) is an oxygenate [$C_6H_{14}O$, or $(CH_3)_3CH_2COCH_3$] that serves as a gasoline additive to boost octane rating and decrease engine knocking (Wallace *et al.*, 2009). Bio-ETBE is produced by reacting isobutylene with ethanol, often using bioethanol to qualify for the biofuel credits available in many countries, such as through Brazil's RenovaBio policy (MF and MP, 2017). This process involves heating the reactants together in the presence of a catalyst, typically an acidic ion exchange resin like AmberLyst (Tretbar *et al.*, 2018).

⊞ 262190 Other biogasolines

Other biogasolines not elsewhere specified.

262200 Biodiesels

Biodiesels are liquid biofuels derived from biomass and can be used in diesel engines. A wide range of biomass feedstocks, including sugary, starchy, cellulosic materials and algal biomass, could be used to produce biodiesels.

⚠ The origin of the alcohol used to react triglycerides opens a debate about the renewable status of biodiesel, since the alcohol can come from fossil fuels. Ideally, the alcohol should come from renewable sources. Regardless, there is an argument that even if the production of biodiesel requires non-renewable reactants, it is only part of the transesterification and the carbon content of the alcohol is not included in the biodiesel, rather it stays in the glycerol by-product of the reaction, with only one hydrogen atom staying in the biodiesel. For practical purposes, IRENA categorises biodiesels with fossil alcohols as renewables, whereas the alcohol production energy sources and transformations are properly accounted for in energy balances.

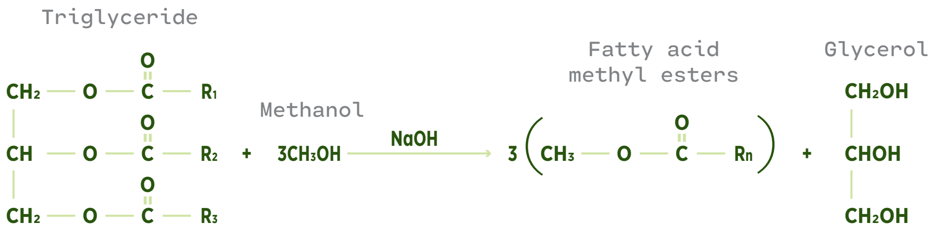
Biodiesels may be blended with petroleum diesel or used directly in diesel engines. This category is subdivided first by the process used to produce the type of biodiesel and second by the type of biomass feedstock used. Transesterified biodiesel (262210) is derived from oils within food crops or from animal fats that undergo a transesterification reaction (it therefore competes with food and crops that would otherwise be consumed by humans or animals); thermal process biodiesel (262220) comes from cellulosic biomass that must undergo thermal distillation to extract oils; and microalgal biodiesel (262230) is sourced from the oils in microalgae that also undergo a transesterification reaction, like transesterified biodiesel, but these oils are sourced without competing with human and animal food and crops. Straight vegetable oil (262240) refers to oils from oil plants or residues that undergo minimal transformation processes after extraction; hydrogenated vegetable oil diesel (262250) can be sourced from multiple feedstocks, as it undergoes multiple processes to get refined into a hydrocarbon that closely resembles fossil fuel diesel.

262210 Transesterified biodiesel

Transesterified biodiesel, also known as conventional biodiesel, is biodiesel produced through a chemical reaction (transesterification) between an alcohol and the triglycerides found in vegetable oils or animal fats, using a catalyst. Transesterified biodiesel is a linear alkyl ester with a flash point of around 150°C and a density of about 880 kg/m^3 (UNSD, 2018). Typically, the process of transesterification combines the oils or fats of biological origin with methanol to produce fatty acid methyl ester and glycerol (Fukuda *et al.*, 2001). Any animal fat or vegetable oil (including inedible oils) can be used to produce transesterified biodiesel, but the most frequently used oils are palm oil, rapeseed (canola) oil and soybean oil.

The length of the hydrocarbon chain for the biodiesel will depend on the length of the triglycerides found in the feedstocks – represented by the 'R' in Figure 19. A length between C_{12} and C_{22} is typical; the shortest chains are found in coconut oil and the longest ones in rapeseed oil (C_{20} and over). The most common lengths are between C_{16} and C_{18} (He and Pryor, 2020).

Figure 19 Transesterification of triglycerides with methanol and sodium hydroxide catalyst to produce biodiesel and glycerol



Note: NaOH is only one of many researched catalysts for this reaction. Likewise, there are many potential alcohol reactants for the reaction. We are showing the use of methanol and sodium hydroxide for illustrative purposes.

The triglycerides must be pretreated to avoid the presence of water, contaminants and free fatty acids. The pretreatment process is outlined below.

Figure 20 Pretreatment of oils to optimise the yield of biodiesel through transesterification

262220 Thermal process biodiesel

Thermal process biodiesel, or second-generation biodiesel, is produced from the thermal transformation of a biomass feedstock and can be used in diesel engines. As shown in Figure 17, the feedstocks for this biodiesel are cellulose-rich. The production process of this advanced biodiesel involves heating biomass in a low-oxygen environment to create gas through gasification. The synthesis gas, or syngas, is then converted and refined into a liquid biofuel with properties like diesel.

Another typical process called hydrothermal liquefaction creates thermal process biodiesel by pressurising biomass feedstocks at high temperatures (Mathanker *et al.*, 2020).

Advanced biodiesel refers to liquid hydrocarbons derived from biomass or renewable waste using thermal processes (262220) or biodiesel generated from third-generation biofuels (262230), which can be used in standard diesel engines with little or no modification.

262230 Microalgal biodiesel

Microalgal biodiesel or third-generation biodiesel is the liquid biofuel produced by microalgae that can be used in diesel engines. Some microalgae produce up to 70% of lipids in weight by fixating carbon during photosynthesis (Ferreira *et al.*, 2019). Some benefits of this advanced biodiesel include the reduced use of farmland since microalgae live in water, a short growth cycle and high yield, and little competition with human food supply (Zhang *et al.*, 2022).

As with other biodiesels, advanced biodiesel is primarily used as a transport fuel, but it can also be used for electricity generation or heating end uses. It can be blended with other fuels or used directly. When blended, energy statisticians should register a transfer or a transformation, from biodiesel to blended diesel.

In energy statistics, the amount of solid biofuels and renewable waste used as primary energy in the manufacturing of advanced biodiesel should be recorded. This would appear as a flow to transformation for each solid biofuel used and a flow from transformation for advanced biodiesel, excluding transformation losses.

262240 Straight vegetable oil

Straight vegetable oil (SVO), also known as VegOil, waste vegetable oil or virgin vegetable oil, is a type of alternative fuel for diesel engines. The term virgin vegetable oil is sometimes specifically used to refer to unprocessed oils that meet certain quality standards. In many cases, this oil may be used for cooking, and then repurposed for energy uses.

While SVO is sometimes used directly in engines, it is more common to first filter vegetable oil used for cooking to remove impurities such as food particles and water (Capuano *et al.*, 2017). This filtered oil is a popular alternative fuel source for diesel engines. It is typically obtained from restaurants or other food service establishments that generate large quantities of used cooking oil.

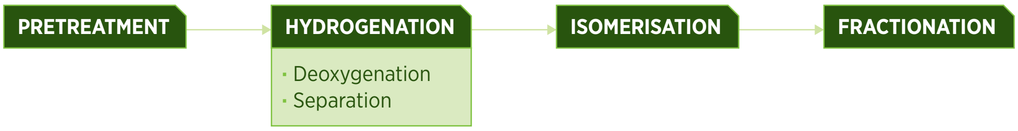
Although SVO is a renewable and potentially sustainable alternative to fossil fuels, its use presents some challenges. Concerns about its availability and cost, as well as its impact on engine performance and emissions, are notable issues (No, 2019). SVO tends to be thicker and more viscous than diesel fuel, which can affect engine performance and potentially damage the engine. It also contains higher levels of contaminants, which can increase emissions and contribute to engine wear (Che Mat *et al.*, 2018). Despite these challenges, using SVO as a fuel source remains a viable option for some diesel engine owners, particularly those with access to a reliable source of waste vegetable oil.

262250 Hydrogenated vegetable oil diesel

Hydrogenated vegetable oil diesel, or renewable diesel, is a blend of hydrocarbons that closely resemble petroleum diesel fuel in terms of properties but are derived from biological sources such as animal fats, used cooking oil, and both edible and inedible crops. On average, its hydrocarbon chain is $C_{12}H_{23}$.

The process for obtaining renewable diesel involves removing impurities from the feedstock during pretreatment, then hydrogenating the purified feedstock with high-pressure hydrogen to eliminate oxygen and separate water; this is followed by isomerisation and fractionation.

Figure 21 Synthesis pathway to produce hydrogenated vegetable oil diesel



Based on: Van Gerpen and He, 2014.

During the hydrogenation process, the fats and oils are saturated with high-pressure hydrogen, resulting in the production of long-chain hydrocarbons, water, carbon dioxide and propane ($CH_3CH_2CH_3$). Although hydrogenation is a common method for producing renewable diesel, other processes (*e.g.* hydrocracking) can also be employed, and the feedstock may include animal fats in addition to vegetable oils.

262290 Other biodiesels

Other biodiesels not elsewhere specified.

262300 Bio-jet kerosenes

Bio-jet kerosene refers to liquid biofuels derived from biomass and blended with or replacing jet kerosene. Commonly, bio-jet kerosene is referred to as sustainable aviation fuel. Bio-jet kerosene can be manufactured from any type of biomass, including plant cellulose and algae. It is produced by a range of thermal processes (including gasification followed by Fischer-Tropsch synthesis or pyrolysis followed by hydrogenation) or by the conversion of sugar to hydrocarbons using micro-organisms such as yeast. Jet fuel is a high-specification fuel that must meet the standards defined in ASTM D1655 for Jet A1 or in the Ministry of Defence Standard 91-91 in the United Kingdom. Bio-jet kerosene must meet these same standards and, in addition, have an ASTM D7566 certification. The ASTM certification procedure is rigorous and can take years and millions of US dollars to complete (IRENA, 2021: 15).

⚠ Bio-jet kerosene must meet the following standards:
1. ASTM D7566
2. ASTM D1655 for Jet A1 or the 91-91 Ministry of Defence Standard in the UK

Bio-jet kerosene may be blended with other fuels or used directly. Where it is blended, energy statisticians should register a transfer or a transformation, from bio-jet kerosene to blended kerosene.

Pathways

There are four certified pathways to produce bio-jet kerosene; others are in development (IRENA, 2017, 2021):

1. Hydroprocessed esters and fatty acids (HEFA) – oleochemical processes. This is the main process used to date. Common feedstocks are oils and fats.

2. Gasification through the Fischer-Tropsch method – thermochemical processes. Common feedstocks include municipal solid waste and woody biomasses.

3. Synthesised iso-paraffinic fuels – biochemical processes.

4. Alcohol-to-jet – hybrid thermochemical or biochemical processes, typically using isobutanol.

262900 Other liquid biofuels

The other liquid biofuels category refers to liquid fuels derived from biomass that are not typically for use in diesel or spark-ignition internal combustion engines or as a substitute for jet kerosene, such as pyrolysis oil. To produce these fuels, thermal processes like gasification are used to convert solid biomass and waste into a range of liquid biofuels with various properties.

262910 Bio-LPG

Bio-LPG (liquefied petroleum gas), also known as renewable propane or bio-propane, is a three-carbon alkane (C_3H_8) produced from renewable feedstocks, including plant and vegetable residues. It is generated through hydrotreatment, which involves reacting vegetable oils or animal fats with hydrogen using a catalyst to produce propane (Johnson, 2019). This process results in a product that has properties equivalent to conventional propane, allowing it to be used in the same applications. It can also be produced biologically, such as through the branched-chain keto acid decarboxylase-dependent pathway (Amer *et al.*, 2020).

⚠ Bio-LPG serves as a more sustainable alternative to fossil LPG, with the potential to significantly reduce carbon dioxide emissions, achieving reductions of up to 80% compared with fossil LPG (SHV Energy, n.d.). Because of its use of hydrogen as raw material through hydrotreatment, the production of bio-LPG could be coupled with an increased production of renewable hydrogen.

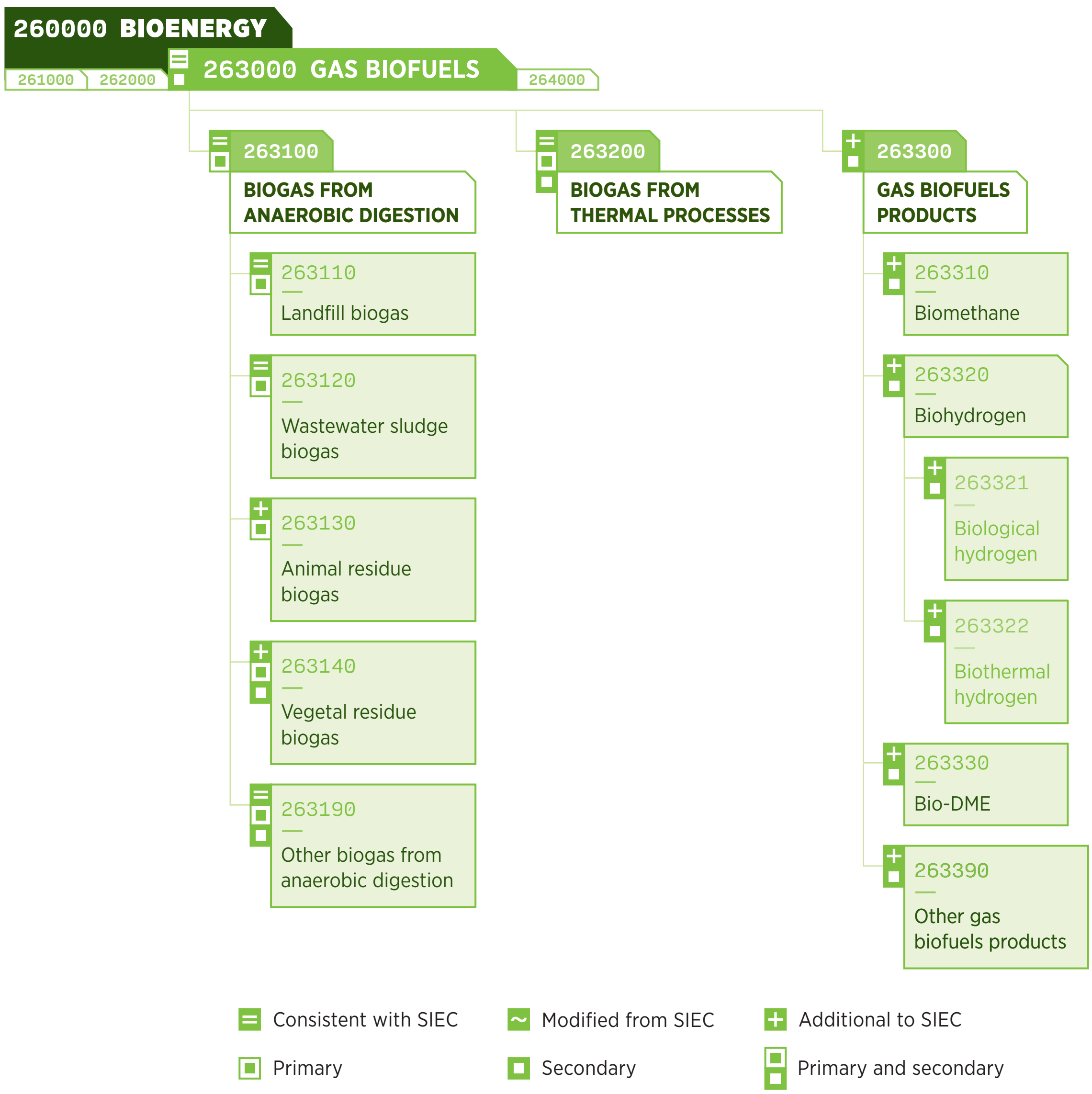
262990 Other liquid biofuels n.e.s.

Other liquid biofuels not elsewhere specified.

263000 Gas biofuels

Gas biofuels are gases produced from the anaerobic digestion or thermal processes of some solid or liquid biofuels and biological residues. They are mostly primary energy products. The divisions into the gas biofuel subcategories are based on a mix between the process used to produce them (*e.g.* anaerobic digestion or thermal processes) and their chemical characteristics (*e.g.* biomethane, biohydrogen). Biogas from anaerobic digestion is primarily composed of methane and carbon dioxide, which can be purified to produce close-to-pure methane gas, the same composition as natural gas. Biogas from thermal processes is generated by gasification or pyrolysis of biomass, resulting in a mix known as synthesis gas (syngas): hydrogen and carbon monoxide. This mixture can be further processed to modify its composition and produce substitute or synthetic natural gas. The gas biofuels aggregate group also includes gas biofuel products, which are secondary gas biofuels produced from various biological sources using different synthesis pathways. Gas biofuel products are secondary energy products.

Figure 22 IRENA classification of gas biofuels



Gas biofuels are primarily used for heat and power production, but they can also serve as a transport fuel and, in small quantities, as a chemical feedstock for non-energy use. When gas biofuels are mixed with natural gas, only the biological component should be considered as renewable energy.

Most gas biofuels are treated as primary energy products, and the energy content of the solid materials used to produce gas biofuels is not recorded in energy balances. Solid biofuels and renewable waste used to manufacture biogas from thermal processes should be shown as a transformation flow, accounting for transformation losses (UNSD, 2018).

Gas biofuels are a promising renewable energy source that can significantly contribute to reducing greenhouse gas emissions. It is estimated that gas biofuel production could reduce greenhouse gas emissions by up to 90% compared with fossil fuel alternatives (Laca *et al.*, 2019). Additionally, gas biofuel production can help reduce the amount of waste sent to landfills and provide a source of renewable energy for local communities.

263100 Biogas from anaerobic digestion

Biogas from anaerobic digestion primarily consists of methane and carbon dioxide (Herout *et al.*, 2011),[11] and the subcategories are classified by their biomass feedstock: landfill biogas (263110), wastewater sludge biogas (263120), animal residues biogas (263130), vegetal residues biogas (263140), and other biogases from anaerobic digestion (263190).

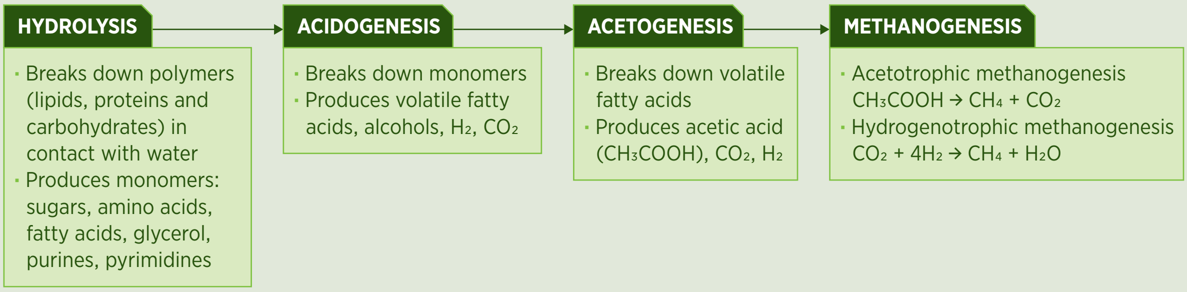
On a large scale, biogases from anaerobic digestion are primarily used for electricity production (including combined heat and power production) or for mixing with natural gas in gas distribution networks. On a small scale, they are more often used to cook (within the heat rising energy sector). When these biogases are blended with other gases, energy statisticians should register this as a transfer or as a transformation from the biogas to the blended gas. If any of the gases are used in the production process, this should be shown as own-use of the gases and not as biogas consumption.

Pathways: Anaerobic digestion is a biochemical process that occurs in low-oxygen environments, where organic matter (made up of the elements C-H-O-N-S) decomposes in contact with water to produce methane and carbon dioxide (biogas). The full process consists of four complex biochemical reactions: hydrolysis, acidogenesis, acetogenesis, and methanogenesis.

[11] *The average volumetric composition of biogas from anaerobic digestion is 55% methane; 42% carbon dioxide; 0.4% oxygen; 100-300 ppm hydrogen sulphide; and traces of water, nitrogen, hydrogen and siloxane.*

Box 2 Anaerobic digestion step by step

Figure 23 Anaerobic digestion process



Based on: Zhang et al., 2016.

Each step is sequential, so the products of a step are the raw materials of the next step. The main reactions for each step are as follows.

Hydrolysis, the first step, in which acidogenic bacteria break down complex carbohydrates, lipids and proteins into their simpler forms. This is also one of the slowest steps in anaerobic digestion.

Equation 1 Main hydrolysis reaction within anaerobic digestion

$$C_6H_{10}O_4 + 2H_2O \rightarrow C_6H_{12}O_6 + H_2$$

Based on: Zhang et al., 2016.

Acidogenesis, the second step, produces various acids (propionic acid, butyric acid and acetic acid) along with hydrogen and carbon dioxide.

Equation 2 Main acidogenesis reactions within anaerobic digestion

$$C_6H_{12}O_6 \longleftrightarrow 2CH_3CH_2OH + 2CO_2$$

$$C_6H_{12}O_6 + 2H_2 \longleftrightarrow 2CH_3CH_2COOH + 2H_2O$$

$$C_6H_{12}O_6 \rightarrow 3CH_3COOH$$

Based on: Bajpai, 2017.

Acetogenesis, the third step, in which acetogenic bacteria produce hydrogen, acetic acid and carbon dioxide.

Equation 3 Main acetogenesis reactions within anaerobic digestion

$$2CH_3CH_2COO^- + 3H_2O \longleftrightarrow CH_3COO^- + H^+ + HCO_3^- + 3H_2$$

$$C_6H_{12}O_6 + 2H_2O \longleftrightarrow 2CH_3COOH + 2CO_2 + 4H_2$$

$$CH_3CH_2OH + 2H_2O \longleftrightarrow CH_3COO^- + 3H_2 + H^+$$

Based on: Bajpai, 2017.

Methanogenesis, the last step, in which methanogenic bacteria use the acetic acid, hydrogen, carbon dioxide and other compounds (*e.g.* formic acid, methanol, carbon monoxide) from previous steps to produce methane. Methanogenesis reactions are highly susceptible to surrounding conditions.

Equation 4 Main methanogenesis reactions within anaerobic digestion

$$CH_3COOH \rightarrow CH_4 + CO_2$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

$$2CH_3CH_2OH + CO_2 \rightarrow CH_4 + 2CH_3COOH$$

Based on: Bajpai, 2017.

This process takes place in all biogases from anaerobic digestion. The distinction IRENA has used for the subcategories is the source of the organic matter.

263110 Landfill biogas

Landfill biogas is produced from the anaerobic digestion of organic matter in landfills. Most landfill biogas is produced by anaerobic digestion, although traces may also come from chemical reactions between waste materials and the evaporation of volatile organic compounds. These landfills must be constructed for the purpose of collecting biogas using pipes or wells built into the sealed landfill (Asgari *et al.*, 2011), but existing landfills could also be retrofitted with a biogas collection system. Any landfill biogas used in the operation of the landfill site (*e.g.* for treating leachate) should be treated as own-use of energy. Landfill biogas can be further upgraded to biomethane (263310) (Dada and Mbohwa, 2017).

263120 Wastewater sludge biogas

Wastewater sludge biogas is produced from the anaerobic digestion of organic matter in wastewater. Wastewater (municipal/domestic) contains suspended solids, biodegradable organics, pathogens, nutrients, pollutants, refractory organics, heavy metals and dissolved inorganic compounds. It is a residue rich in organic matter that is mostly treated to produce clean water, as well as biogas as a by-product.

The biogas is produced by allowing the residue from the wastewater treatment process, also known as sludge, to undergo anaerobic digestion. The biogas is removed during the process, although some may be burned for own-use of energy (*e.g.* to heat the biodigester tanks and accelerate the anaerobic digestion process).

The sludge can be processed in different ways: at wastewater treatment plants, in wetlands and in septic tanks.

In **wastewater treatment plants**, sludge comes from the bottom of settling tanks during the primary and advanced primary treatment steps (Nguyen *et al.*, 2021). In **wetlands**, sludge comes from surface (rooted or floating plants) or subsurface (horizontal or vertical) flow designs, where wastewater is filtered by plants. The bottom layer of wetlands is anaerobic, allowing anaerobic digestion to occur and releasing biogas onto the surface. **Septic tank** wastewater can also produce biogas through anaerobic digestion. These septic tanks are common in rural areas and are especially useful in tropical regions (Sikora, 2021).

263130 Animal residue biogas

Animal residue biogas is biogas from the anaerobic digestion of animal residues, including manure, other bodily fluids, and corpses. Animal residues can be filtered for large solids, then processed through anaerobic digester tanks.

263140 Vegetal residue biogas

Vegetal residue biogas is the biogas produced from the anaerobic digestion of any vegetal residue, including agricultural residues, crop residues and harvest residues. Where the residues come from vegetation used for energy purposes, these biogases should be considered secondary energy products.

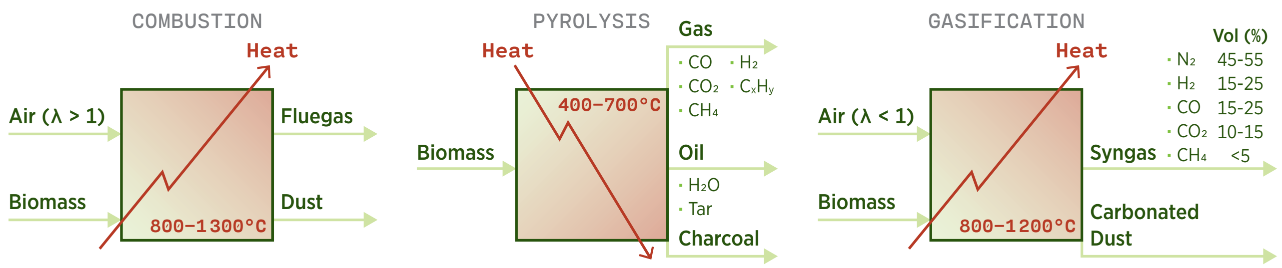
263190 Other biogas from anaerobic digestion

Other biogases from anaerobic digestion are biogases produced from all other organic matter not elsewhere specified. Depending on the biomass feedstock, these biogases could be primary or secondary energy products.

263200 Biogas from thermal processes

Biogas from thermal processes, also known as synthesis gas (or syngas), is mostly produced by the pyrolysis or gasification of solid biomass. Less commonly, it can be a by-product of incomplete combustion.

Figure 24 Common biomass thermochemical processes to produce biogas/syngas



Based on: Solarte-Toro et al., 2021.

Notes: CH_4 = methane; CO = carbon monoxide; CO_2 = carbon dioxide; C_xH_y = hydrocarbons; H_2 = hydrogen; H_2O = water; N_2 = nitrogen.

In **combustion**, the biomass is burned at high temperatures inside a combustion chamber that is fed with a stoichiometric excess of air ($\lambda > 1$). The full combustion reaction produces water and carbon dioxide, but often there are incomplete and by-product reactions in combustion as well. Combustion is mostly used to generate heat, but in some cases the gases produced from the reaction are separated and upgraded to other biogases. Dust is also a by-product, which is composed of coarse fly ash and aerosols smaller than 100 μm. Coarse fly ash has metal components and organic components from incomplete combustion. Aerosols are solid and liquid particles suspended in the gas.

Equation 5 Simplified combustion reactions of biomass

Overall reaction

$$CmHn + (m + n/4)O_2 \rightarrow mCO_2 + n/2H_2O$$

By-product reactions by component

$$2C + O_2 \rightarrow 2CO$$ Carbon

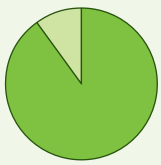
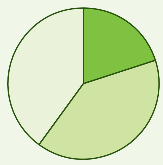
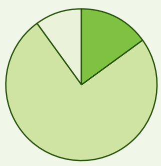
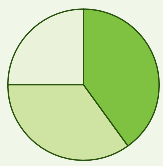
$$2X + H_2 \rightarrow 2HX$$ Halogens

$$N_2 + xO_2 \rightarrow 2NO,\ 2NO_2,\ N_2O$$ Nitrogen (NO_x)

$$S + O_2 \rightarrow SO_2\ ;\ \text{and}\ 2SO_2 + O_2 \rightarrow 2SO_3$$ Sulphur (SO_x)

In **pyrolysis**, biomass reacts with heat at lower temperatures than combustion, with little to no air to avoid oxidation reactions. Without oxygen, the biomass is distilled into charcoal, pyrolysis gas and pyrolysis oils. These gases and oils can be used to produce other bioliquids or biogases or burned in the process to be used as a partial heat source for the pyrolysis. The ratio of solids, liquids and gases produced in pyrolysis is highly dependent on the pyrolysis temperature and the residence time of reaction. The faster the pyrolysis, the larger the amounts of gases produced.

Table 3 Pyrolysis conditions for different physical states

Pyrolysis conditions	Fast reaction	Slow reaction
High temperature	90% gas 10% liquid 	20% gas 40% liquid 40% solid 
Low temperature	15% gas 75% liquid 10% solid 	40% gas 35% liquid 25% solid 

Based on: Kerihuel, 2018.

In **gasification**, biomass is reacted with heat and a little oxygen (λ < 1), producing carbonated dust and biogas from thermal processes. Gasification technologies usually have combined zones of reactions, where there is reduction of carbon, combustion, pyrolysis and drying all in one chamber or set of reactors.

Biogas from thermal processes is mostly composed of carbon monoxide, carbon dioxide and hydrogen, but it may also include other gases, such as methane and nitrogen. Synthesis gas can be manufactured from any type of biomass or renewable waste, and its composition depends on the type of biomass used to make the gas and the thermochemical pathway used.

Synthesis gas can be used for many purposes, including the production of electricity (including combined heat and power) or the manufacture of biomethane, advanced liquid biofuels and other chemicals for non-energy uses. Biogases from thermal processes category excludes all these uses except the use of synthesis gas to produce electricity (including combined heat and power) or biomethane. If biogas from thermal processes is used to manufacture biomethane, then energy statisticians should only report the energy content of the biogas within the total energy content of the biomethane This could be done by including a transformation energy flow.

⊞ 263300 Gas biofuels products

Gas biofuels products is an aggregate group including secondary energy products mostly stemming from biogas from anaerobic digestion or biogas from thermal processes. Its subdivisions are categorised by the chemical composition of each gas biofuel product: the biological feedstock undergoes a chemical or physical transformation process to produce biomethane, biohydrogen, biodimethyl ether and other biogas products not elsewhere specified.

⊞ 263310 Biomethane

Biomethane is a secondary energy product derived from various organic materials – commonly from either synthesis gas or biogases from anaerobic digestion – and is chemically identical to the methane found in natural gas.

Upgrading biofuels to biomethane involves multiple physical processes. For instance, upgrading biogas from anaerobic digestion requires separation processes such as water scrubbing (absorption), pressure swing adsorption, membrane separation or chemical absorption, which remove impurities such as carbon dioxide, water, nitrogen, oxygen, siloxane and other volatile compounds. By doing so, the methane part of biogas from anaerobic digestion can be selectively isolated, making it suitable for use as a renewable substitute for natural gas.

Biomethane has various applications. It can be mixed with natural gas in existing pipelines, or it can be combusted to generate electricity. It can also be burned for heating and transportation (Koonaphapdeelert *et al.*, 2019; Quintino *et al.*, 2021).

263320 Biohydrogen

Biohydrogen is hydrogen produced from biological feedstocks. Biohydrogen serves as an aggregate group for hydrogen produced via either biological processes (biological hydrogen) or biothermal processes (biothermal hydrogen).

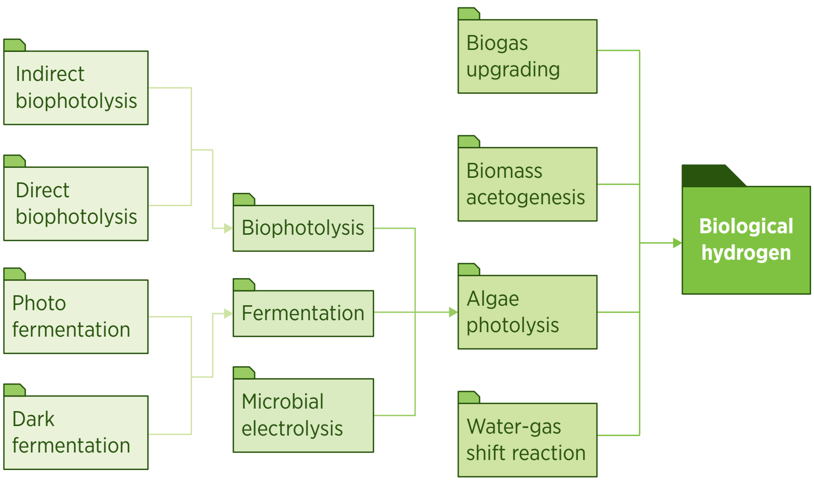
263321 Biological hydrogen

Biological hydrogen is hydrogen produced via biological processes, primarily anaerobic digestion, specifically during the acetogenesis step. In this subprocess, micro-organisms produce hydrogen by digesting organic matter anaerobically.

Lately, researchers have explored other methods for biological hydrogen production, including biophotolysis, which involves using sulphur-deprived algae to produce hydrogen via photosynthesis. Under specific conditions, algae synthesise hydrogen, using sunlight as a source of energy. Other methods for biological hydrogen production include dark fermentation, photofermentation and microbial electrolysis cells. These approaches harness the abilities of various micro-organisms to produce hydrogen under different conditions. While biological hydrogen is a growing area of research, its production is still at a laboratory scale.

Figure 25 summarises some synthesis pathways for biological hydrogen.

Figure 25 Synthesis pathways to produce biological hydrogen

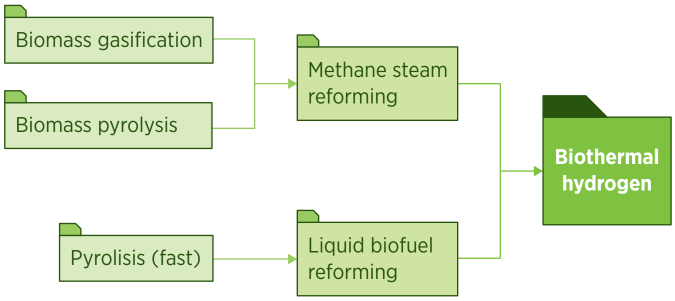


263322 Biothermal hydrogen

Biothermal hydrogen is hydrogen derived from thermal processes to upgrade biofuels.

Biothermal hydrogen is a secondary energy product, and as such, energy statisticians should record the primary energy of its biomass source (*e.g.* wood fuel, energy crops, other harvested biomass, or harvest residues) and its corresponding energy transformation into biothermal hydrogen.

Figure 26 Synthesis pathways to produce biothermal hydrogen



Based on: Younas et al., 2022.

Methane steam reforming involves the steam reforming reaction for biomass gasification and biomass pyrolysis syngas, followed by the water-gas shift reaction to produce hydrogen and carbon dioxide and, finally, adsorption to remove the carbon dioxide from the mixture. Methane steam reforming pathways (biomass gasification, biomass pyrolysis) have lower hydrogen yields – between 35 mol and 6 mol of biomass are needed for each kilogramme of hydrogen produced (Nanda *et al.*, 2016; Pala *et al.*, 2017) – than other fossil fuel pathways. The best yields are reported using wheat straw as a feedstock in a tubular batch reactor running at 500°C and using a Nickel nanocatalyst.

Liquid biofuel reforming uses the biofuel produced from fast pyrolysis in a steam reforming reaction to produce carbon monoxide and water, followed by processing through a water-gas shift reaction to produce hydrogen and carbon dioxide and, finally, adsorption to remove the carbon dioxide from the mixture. Common feedstocks for this pathway include wastewater sludge, biomass processing residues and energy crops. To optimise hydrogen production, the pyrolysis benefits from high temperatures, the addition of a catalyst and a relatively long reaction time (Fahmy *et al.*, 2020).

253330 Bio-DME

Bio-dimethyl ether (bio-DME), also known as methoxymethane, wood ether, dimethyl oxide or methyl ether, is an ether with the chemical formula C_2H_6O. It is a colourless, slightly narcotic, non-toxic, highly flammable gas at ambient conditions, but it can be handled as a liquid when lightly pressurised (ETIP Bioenergy, n.d.).

Bio-DME is a secondary product that uses carbon dioxide as a synthesis input, where the carbon comes from biological sources. An example would be the gasification of biomass to produce carbon dioxide and then the use of a single-step synthesis process, such as those with JFE technology or Hardlor Topsoe technology (Ju *et al.*, 2009; Marchionna *et al.*, 2008).

Chemically, bio-DME has similar properties to liquefied petroleum gas and releases small amounts of pollutants upon combustion (Kabir *et al.*, 2013), placing it as a significant potential replacement for fossil-based fuels. Rising interest about bio-DME stems from its potential use to heat industrial processes, replace liquefied petroleum gas in boilers for electricity generation, replace diesel in internal combustion engines upon retrofitting and serve as a hydrogen carrier (International DME Association, n.d.).

263390 Other gas biofuels products

Other gas biofuels products not elsewhere specified.

264000 Renewable waste

Renewable waste is an aggregate group comprising renewable municipal waste and renewable industrial waste.

⚠ Post-consumer wood waste (recovered wood products) used for energy may be included as part of renewable municipal or industrial waste, but where detailed statistics are available these amounts may be classified as other solid biofuels (261900) so long as there is no double-counting (*i.e.* these amounts can only be counted in one category).

264100 Renewable municipal waste

Renewable municipal waste is municipal solid waste of biological origin that is used for energy. Municipal solid waste is collected from households and enterprises and is generally mixed, although waste of different types may be collected separately or sorted as part of the waste disposal process. Renewable municipal waste is the proportion of this total amount of waste that is of biological origin; it includes waste materials such as discarded food, paper and cardboard, disposable nappies, wooden articles, textiles, rubber and leather, and gardening waste.

⚠ Non-wood materials should be estimated as a proportion of the waste and excluded. Where information is not available, the renewable portion of total municipal solid waste is usually assumed to be 50% of the total (in terms of energy content).

Renewable municipal waste is a primary energy source used to generate electricity and produce heat for sale or direct use, most likely by burning the waste in incinerator facilities. However, renewable municipal waste may also be processed into secondary fuels, such as refuse-derived fuel or solid recovered fuel, and these products may be used in other power plants (*e.g.* for co-firing with coal). Renewable municipal waste may also be transformed into advanced liquid biofuels.

Secondary biofuels derived from waste (such as refuse-derived fuel and solid recovered fuel) are produced by shredding and dehydrating municipal solid waste and removing non-combustible materials in the process. They may then be sold without further processing or compressed into pellets or briquettes. These fuels may be produced to very precise specifications (in terms of total energy and bioenergy content, particle size, moisture content, *etc.*). In the case of solid recovered fuel, there are international standards for the specification and measurement of such variables.

Secondary biofuels derived from waste are not currently identified as separate products in energy statistics but are included under the general heading of renewable municipal waste. In addition, if secondary biofuels are processed into pellets and briquettes, they should be classified as biomass pellets and briquettes with a corresponding use of renewable municipal waste as a primary energy input to this transformation process.

⚠ There is no strict rule about what should be classified as renewable municipal waste or as other types of waste. However, all waste used for energy should be reported in only one place to avoid double-counting.

Renewable municipal waste contains primary biofuels that could be classified elsewhere (*e.g.* fuelwood, wood waste, and other vegetal and agricultural waste). Wherever possible, these primary biofuels should be reported under the appropriate heading. The identification of different types of waste in energy statistics is likely to depend on the amount of waste sorting that occurs and the data collected from waste disposal firms.

264200 Renewable industrial waste

Renewable industrial waste is waste materials or heat of biological origin generated by industrial processes that can be used as a source of energy. If it is possible to classify the biological type of the waste, these energy products should be categorised within their own bioenergy section. The renewable industrial waste category serves as a group of unclassified products from industrial processes for which it is unfeasible to classify the type of energy product.

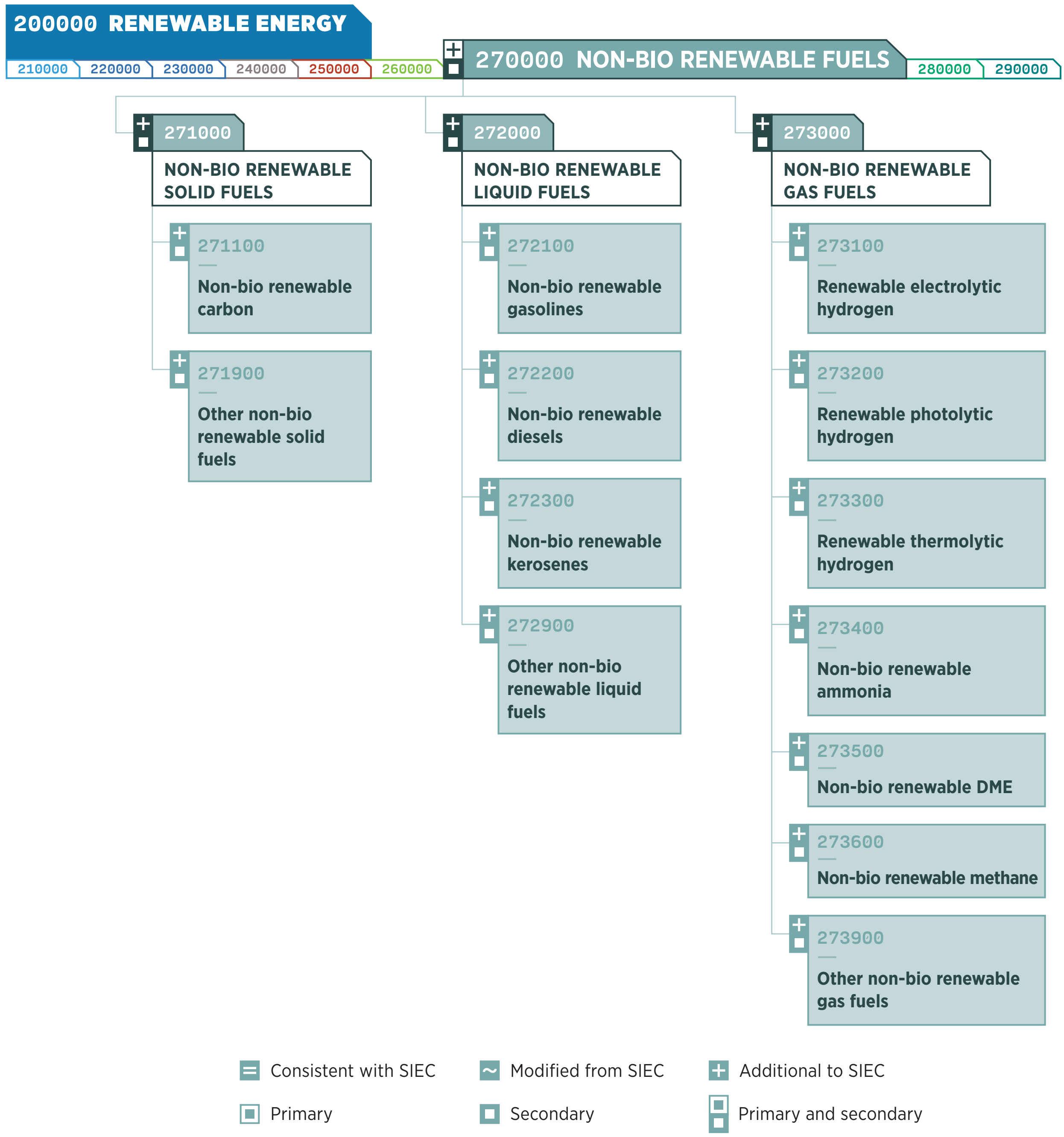
⚠ Each country has different waste management classifications and logistics, so industrial waste could be classified differently across countries. Special attention should be paid to improving the classification of industrial waste accounting.

270000 NON-BIO RENEWABLE FUELS

Non-bio renewable fuels are secondary products further subdivided by their physical state: solid, liquid or gas. This group includes many of the synthetic fuels produced by renewable energy or substances that are not classifiable under a specific renewable energy due to the complexity of their sources.

⚠ This category serves more specifically as an aggregate for synthetic fuels produced with electricity, water, atmospheric carbon and other materials themselves produced with renewable energy not elsewhere specified or with multiple types of renewable energy that are not specified.

Figure 27 IRENA classification of non-bio renewable fuels



Non-bio renewable fuels span the entire chain of renewable energy types. If renewable fuels are synthesised from a specific energy or fuel, they should be reported within that energy source and not in non-bio renewable fuels (270000). But in special cases, the renewable energy type for a fuel cannot be determined due to accounting issues, multiple energy types used in its synthesis, or non-energy sources. In that case, those fuels should be categorised under non-bio renewable fuels.

For example, biohydrogen is included under bioenergy because its energy source is biomass feedstock; renewable electrolytic hydrogen, however, is included in this section (non-bio renewable fuels) because its energy source is electricity produced by renewables. Furthermore, this electricity could come from a single technology or energy type (*e.g.* electricity from solar PV) or a mix of technologies (*e.g.* electricity stored in batteries from a solar or wind mini-grid) or could be calculated as a share of electricity generation in the grid. If the source of electricity is known for each fuel-producing energy source, electricity generation could be assigned to its energy source when building a commodity-energy balance, either in primary production or within power plant/heat plant/combined heat and power plant transformations.

The hydrocarbons in non-bio renewable fuels should come from unspecified renewable sources, such as atmospheric carbon dioxide and renewable electrolytic hydrogen. While atmospheric carbon dioxide cannot be attributed to a specific energy source, it is considered as renewable when used to produce fuels, partly because once it is in the atmosphere, it is within the short carbon cycle of the biosphere.

⊞ 271000 Non-bio renewable solid fuels

Non-bio renewable solid fuels is an aggregate group for solid state renewable synthetic fuels.

⊞ 271100 Non-bio renewable carbon

Non-bio renewable carbon is the solid carbon derived from non-bio renewable sources, for example carbon dusts gathered from atmospheric carbon dioxide. This category excludes any carbon from fossil fuels or from carbon capture technologies that get carbon from fossil fuels or biofuels.

⊞ 271900 Other non-bio renewable solid fuels

Other non-bio renewable solid fuels not elsewhere specified.

⊞ 272000 Non-bio renewable liquid fuels

Non-bio renewable liquid fuels is an aggregate group for liquid state renewable synthetic fuels.

⊞ 272100 Non-bio renewable gasolines

Non-bio renewable gasolines are liquid fuels used in spark-ignition internal combustion engines that are synthesised with renewable non-bio hydrocarbons, such as atmospheric carbon. If the carbon is captured from the combustion of fossil fuels or biomass, such gasoline should be categorised as motor gasoline (114552) or as a type of biogasoline (262100), as appropriate.

272200 Non-bio renewable diesels

Non-bio renewable diesels are liquid fuels used in diesel engines that are synthesised with renewable non-bio hydrocarbons, such as atmospheric carbon. If the carbon is captured from the combustion of fossil fuels or biomass, such diesel should be categorised as gas oil/diesel oil (114571) or as a type of biodiesel (262200), as appropriate.

272300 Non-bio renewable kerosenes

Non-bio renewable kerosene refers to liquid fuels that are blended with or replace jet kerosenes and that are synthesised with renewable non-bio hydrocarbons, such as atmospheric carbon. If the carbon is captured from the combustion of fossil fuels or biomass, such kerosene should be categorised as kerosene-type jet fuel (114561) or as bio-jet kerosene (262300).

272900 Other non-bio renewable liquid fuel

Other non-bio renewable liquid fuels not elsewhere specified.

273000 Non-bio renewable gas fuels

Non-bio renewable gas fuels is an aggregate group for gas state renewable synthetic fuels.

273100 Renewable electrolytic hydrogen

Renewable electrolytic hydrogen is hydrogen produced using electricity from renewable energy sources as fuel in the redox reaction of water electrolysis. This excludes hydrogen stocks used as chemical reactants.

The classification of renewable electrolytic hydrogen is like that of non-renewable electrolytic hydrogen, where the synthesis process and the renewable aspect of the electricity source defines the hydrogen's status as renewable or non-renewable. This classification highlights the importance of electricity as the main fuel source of electrolytic hydrogen.

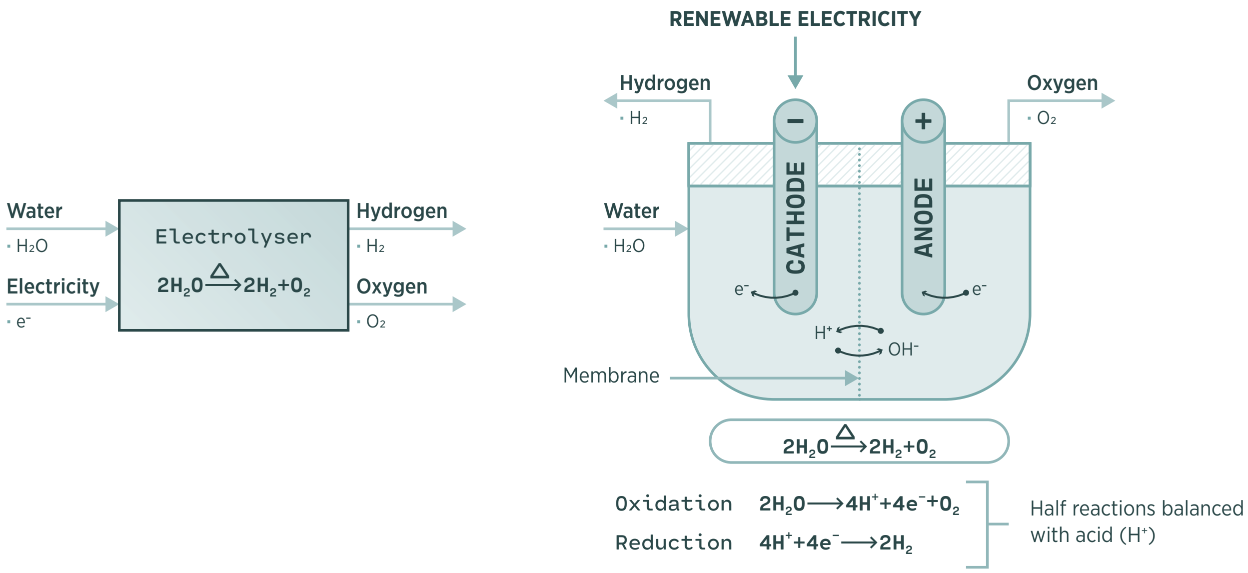
⚠ Because renewable electrolytic hydrogen is a secondary product, there should be a record of the following: the electricity generated by renewables, that electricity as an input to the electrolysis transformation process, a hydrogen output from the transformation, and an end-use consumption of hydrogen.

For commodity balance purposes, hydrogen could be classified as one single commodity, regardless of its renewable or non-renewable status.

The electrolysis of water is an endothermic reaction (needs energy to happen). Two metals (electrodes) are submerged in water, separated by a membrane. Electricity flows into one of the electrodes (cathode) and into the water, starting the electrolysis reaction. Then, electricity flows across and into the other electrode (anode). Hydrogen is produced at the cathode, while oxygen is produced at the anode.

Figure 28 shows a simplified diagram of water electrolysis (left side) and a more detailed diagram with a proton exchange membrane (right side), including the redox reaction and its half-reactions balanced with acid.

Figure 28 Water electrolysis with a proton exchange membrane



To decompose water, electricity flows through a cathode. This energy oxidises water to produce oxygen gas, electrons and hydrogen ions. The hydrogen ions pair up with the electrons and are reduced to hydrogen gas, leaving oxygen and hydrogen gases as products of the electrolysis. Electrolysis (especially alkaline electrolysis) is highly energy efficient at ranges close to 70% (Shiva Kumar and Himabindu, 2019) when comparing the lower heating value of the produced hydrogen against the electricity input required to produce it (Xia *et al.*, 2023).

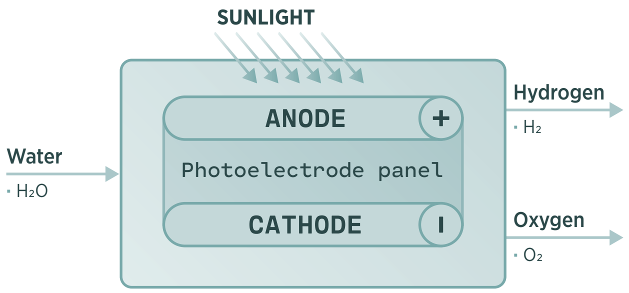
273200 Renewable photolytic hydrogen

Renewable photolytic hydrogen is hydrogen produced using photoelectrochemical light systems that power water electrolysis.[12] Semiconductor photoelectrodes submerged in an aqueous electrolyte can produce sufficient electricity for water electrolysis (Hand, 2008).

[12] *Other compounds have also been used as raw material instead of water: glycerol solutions and water-ethanol solutions.*

Figure 29 shows a simplified version of photoelectrochemical hydrogen production.

Figure 29 Photoelectrochemical hydrogen production with a photoelectrode panel



Photoelectrochemical hydrogen production is still in the research and development stages and has a very low efficiency of around 0.06% (Shiva Kumar and Himabindu, 2019).

273300 Renewable thermolytic hydrogen

Renewable thermolytic hydrogen is hydrogen produced from the thermal decomposition of water into hydrogen and oxygen. With enough heat to reach temperatures of 500-2000°C, and with the help of chemicals, water can be dissociated into its components: hydrogen and oxygen. Despite issues in this process, like corrosion and element toxicity, thermolysis shows promising energy efficiencies of between 20% and 45% (Shiva Kumar and Himabindu, 2019).

⚠ This type of technology is particularly useful in combination with high-temperature renewable energy, such as concentrated solar power.

A variation of this type of hydrogen is renewable plasmolytic hydrogen. Renewable plasmolytic hydrogen is hydrogen produced by plasmolysis (also known as plasma reforming) of renewable feedstock: water, glucose, biomethane, ethanol, and air, among others (Younas *et al.*, 2022). Plasmolysis is the process where water vapour is dissociated into hydrogen and oxygen gas inside a microwave, electrical corona discharge, or dielectric barrier discharge reactor. Where the plasmolysis occurs inside an aqueous solution, the generation of micro-bubbles could help to separate hydrogen gas from oxygen that would dissolve more selectively into the solution (Younas *et al.*, 2022). The yield of hydrogen with plasmolysis has varied between 0.3 gH_2/kWh and 20 gH_2/kWh and has shown energy efficiencies of almost 80% (Rehman *et al.*, 2013).

273400 Non-bio renewable ammonia

Non-bio renewable ammonia refers to all the ammonia produced for energy purposes when using hydrogen from any of the renewable hydrogen pathways.

Renewable ammonia could displace fossil fuels at scale in hard-to-abate areas of the electricity and transport sectors. However, the use of ammonia as a fuel could increase emissions of nitrogen oxides (NO_x and N_2O), which must be avoided.

Ammonia can be produced by reacting hydrogen with atmospheric nitrogen. When the hydrogen comes from renewable sources, the ammonia is considered renewable. Renewable ammonia could play a significant role in the replacement of fossil fuels in the energy system as well as in the agricultural sector, since around 85% of ammonia produced in the world is used to produce fertiliser (IRENA, 2022b). However, in these cases, the ammonia should not be categorised as an energy end-product and should be considered as non-energy end use in energy balances.

Ammonia is a versatile fuel for stationary power and heat and for maritime transport, and it can be used in internal combustion engines, gas turbines, industrial furnaces, generator sets and fuel cells. It can be stored as a liquid at (a) a pressure of at least 8 bar and ambient temperature or (b) atmospheric pressure and -33°C (IRENA, 2022b).

273500 Non-bio renewable DME

Non-bio renewable dimethyl ether (DME) is the same molecule as bio-DME (263330). The distinction in the current category is that non-bio sources are used for DME production. For instance, non-bio renewable DME could be synthesised using industrial waste or captured atmospheric carbon dioxide.

273600 Non-bio renewable methane

Non-bio renewable methane refers to the methane molecule synthesised using renewable carbon and hydrogen from non-bio sources.

273900 Other non-bio renewable gas fuels

Other renewable synthetic gas fuels not elsewhere specified.

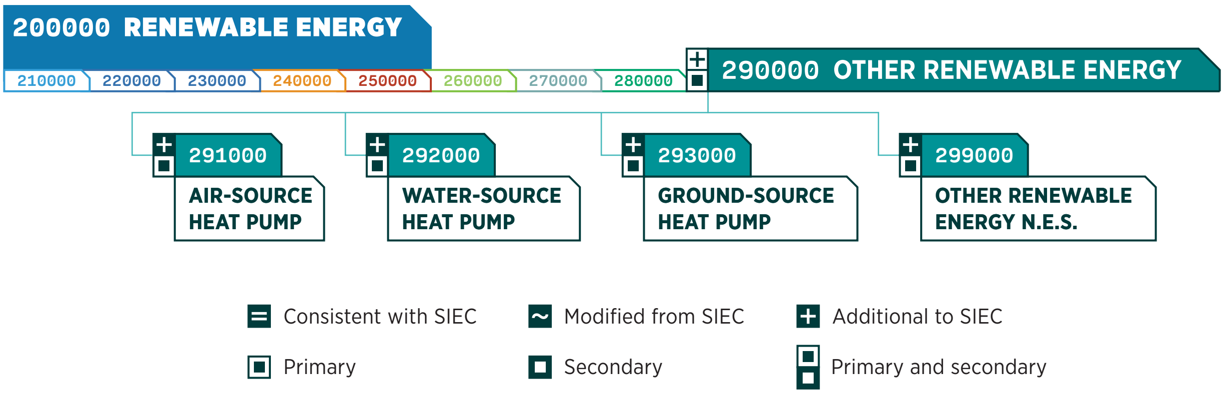
280000 MULTIPLE RENEWABLES

The multiple renewables category is used when there is more than one renewable energy in a mix that is not specified (for instance, in the categorisation of financial data for renewables and where specific renewable technologies are not specified).

290000 OTHER RENEWABLE ENERGY

Other renewable energy includes heat from heat pumps and energy produced from fuel cells (where the fuel for those cells comes from renewable sources).

Figure 30 IRENA classification of other renewable energy



Note: n.e.s. = not elsewhere specified.

Heat pumps are devices in a thermodynamic cycle that transfer ambient heat from one place to another. Most heat pumps use a vapour-compression cycle driven by electricity (or, sometimes, natural gas). The cold vapour in the pump absorbs ambient heat from the heat sink (usually the external environment) then releases it when the vapour is compressed in the place where the heat is required. In this way, heat pumps can move heat from colder areas to warmer areas. Heat pumps are used to heat air or water and can use external air, water or the ground as heat sources. The heat obtained from the external source comes from the natural environment (ambient heat), so it is a source of renewable energy.

The heat energy provided by a heat pump is greater than the energy used to operate the pump, and the former divided by the latter is the coefficient of performance (COP) of the device. The COP of a heat pump varies, depending on the type of energy used to drive the pump, the temperature of the heat source and the temperature required in the destination for the heat. For pumps driven by electricity, the COP for air-source heat pumps is generally about 2.5 for many existing buildings and around 3.0 for newer buildings. And for ground-source and water-source pumps, it can be 3.3 for existing buildings and more than 4.0 for newer buildings (IRENA, 2022c). For pumps driven by natural gas, the COPs are usually about half these amounts.

The renewable (heat) energy produced by a heat pump can be calculated as the rated capacity of the pump, multiplied by the number of hours it operates at full capacity, multiplied by (1 – 1/COP).[13] This calculation results in the amount of ambient heat energy produced (from the external environment) less the energy required to operate the pump. If necessary, an adjustment should also be made in the calculation to subtract any other non-renewable energy used in the pump (*e.g.* for increasing the final heat output of the device).

At present, most energy statistics treat heat pumps as devices that transform electricity into heat (similar to electric boilers) and only include data for (heat) energy from heat pumps if the heat is distributed to a third party. However, as these devices produce more energy than they use, the heat output contains both transformed energy (from electricity to heat) and renewable heat energy. In addition, many heat pumps are used outside the energy sector to produce heat for own-use, so the current convention underestimates the total amount of renewable energy produced by heat pumps.

For correct reporting of the renewable energy from heat pumps, it is recommended that energy from commercial heat pumps should continue to be treated as a transformation activity, but with the heat output divided into the output from transformation (at 100% conversion efficiency) and the remainder recorded as other renewable energy. Renewable heat from all other heat pumps should be calculated as described above and added to this, to give the total production of renewable energy from heat pumps.

⊞ 291000 Air-source heat pump

Air-source heat pumps use the ambient air's temperature as a source of heat or as a heat sink for the pump's operation, depending on the ambient temperature and the need to heat or cool the other end of the thermodynamic cycle. If a pump can do both, it is referred to as a reversible heat pump.

Air-source heat pumps are the most widely used heat pumps. Their efficiency depends on the ambient air's temperature, and because this varies throughout the year, seasons and even days, their thermal efficiency varies throughout their operational use.

⊞ 292000 Water-source heat pump

A water-source heat pump is a device that transfers space heat to or from lakes, ponds, rivers and oceans. Unlike air-source heat pumps, ambient temperature varies less in water sources, making water-source heat pumps a more predictable choice for thermal energy exchange throughout the year. Their thermodynamic cycle can be open loop or closed loop. In open-loop systems, the extracted water flows through the heat exchanger and returns colder to its source. Closed-loop systems involve submerged heat exchanger coils or plates in the water body, transferring heat without contact between the water and the working fluid.

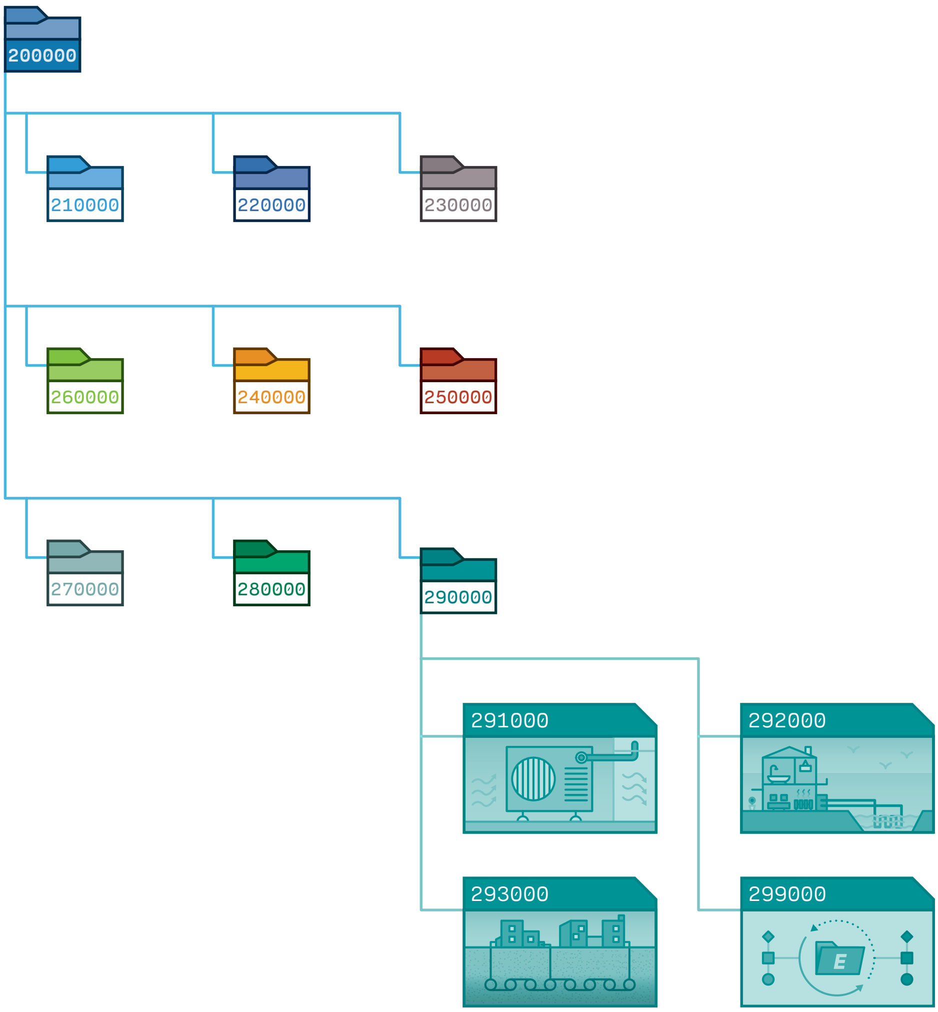
[13] *To account for seasonal differences in use, the number of hours that a pump is actually used (at different settings) should be converted to the (equivalent) number of hours at full capacity that would give the same total heat output.*

⊞ 293000 Ground-source heat pump

Ground-source heat pumps are devices that use the almost constant temperature of the ground (at shallow depths beneath the surface) to heat spaces and/or water when it is warmer underground and to cool spaces when it is colder underground. Like water-source heat pumps, ground-source heat pumps benefit from the year-round stability of the ground's temperature. Ground-source heat pumps can be installed as horizontal loops or vertical loops. Horizontal loops are placed in trenches at a depth of 1 m to 2 m below the ground, while vertical loops are installed in boreholes that can be hundreds of metres deep. Ground-coupled heat exchangers are more common for household and larger (commercial and industrial) buildings.

⊞ 299000 Other renewable energy n.e.s.

Other renewable energy not elsewhere specified.



300000
ENERGY STORAGE

Energy storage is an aggregate category comprising the different ways to store energy for later use, varying from microseconds to months or years. All energy storage categories could be traced back to their renewable or non-renewable sources in theory, but because of the difficulty of doing so, IRENA introduces them as a separate group in this taxonomy.

⚠ The energy storage category excludes fuel storage options that are traditionally treated as stocks, including coal, oil, natural gas and biofuels along with their products. More precisely, the category aims to include storage options that seek to support energy transition technologies and energy carriers.

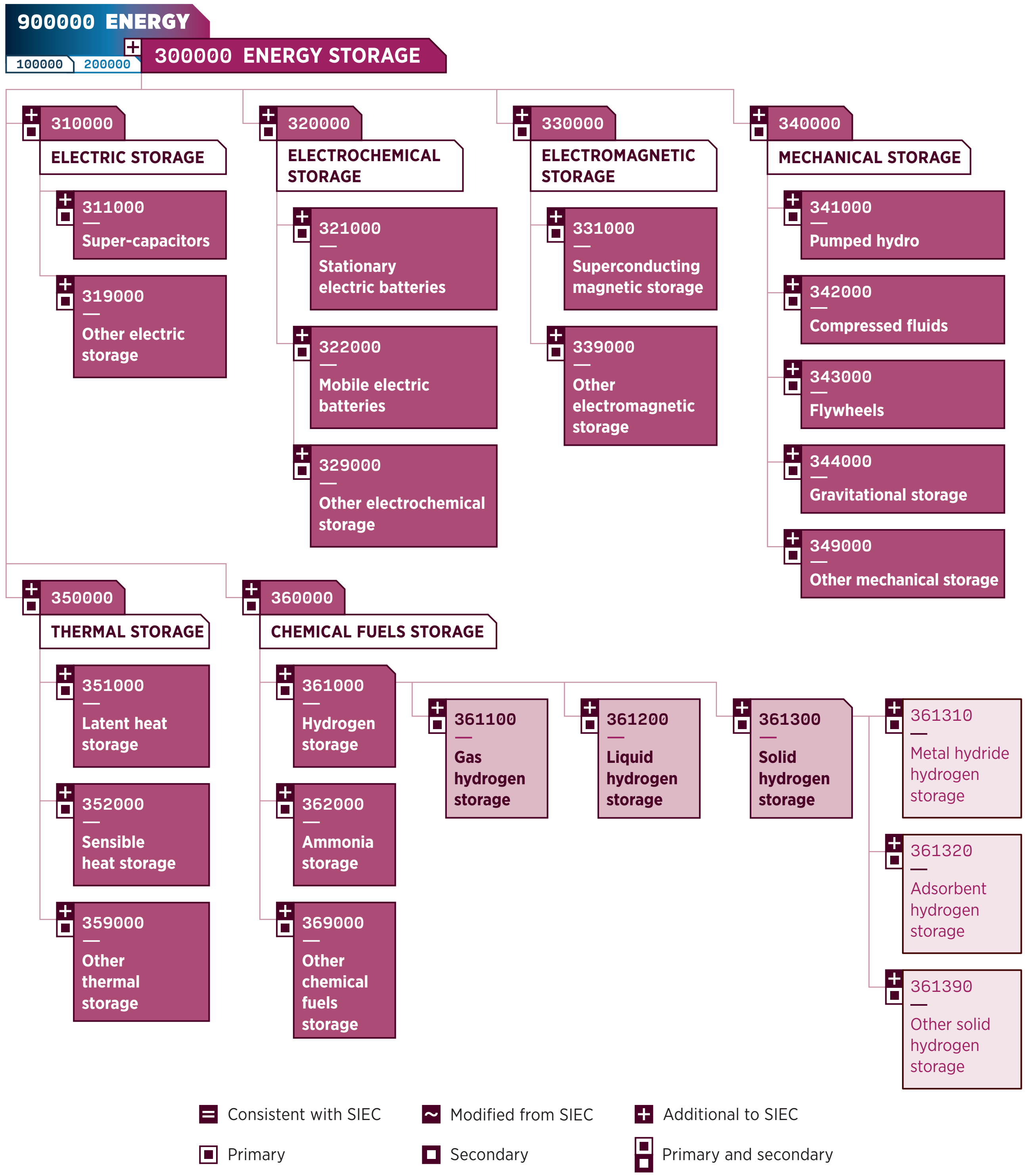
For energy statistics, energy storage has grown in relevance as synthetic fuels and the storage of electricity and heat gain momentum in different countries, particularly those with increasing shares of variable renewable electricity, thereby blurring the line between energy carriers and energy storage options (such is the case with hydrogen and ammonia). For energy storage purposes, energy carriers should only be included as energy storage options if the carriers are being used specifically for energy storage purposes. This would exclude the “storage” of energy in carriers when they are being transported or when they are being physically transformed (*e.g.* compression and decompression of gases or liquids). In the latter, any energy losses should be recorded within the energy transformation block of an energy balance. The Eurostat methodology for the hydrogen commodity balance already pioneers a standard for international energy statistics, where hydrogen storage data is asked for in statistical questionnaires, including storage levels, types of storage and capacities.

Energy balances already include a storage category, referred to as “stocks”. But this category is often reserved for large quantities of coal, oil, natural gas and biofuels, along with their products. But other energy types can be stored for long periods of time; therefore, updates to energy statistics are needed to include these storage options. Furthermore, all energy storage options incur energy losses throughout the process: at energy input, during energy transformation and at energy output. These losses would need to be considered in energy balances, depending on how the energy is being used. Conventionally, energy storage over months or years has been referred to as “stock changes” in an energy balance – particularly for fossil fuels and biofuels – but this often implies that there is a physical stock of fuel, which is not always the case. In cases where energy is stored within a transformation process for a short period of time, it should be recorded as transformational losses or as energy sector own-use depending on the type of process and energy usage.

⚠ The subcategories for energy storage should be reported under energy storage only when the purpose of using the storage technology is to store energy for later use, not when the purpose is to use the energy carriers as fuels or as inputs or outputs of the energy system.

In IRENA's proposed structure for energy storage options, each option has its own set of benefits and challenges, including operational conditions, energy storage efficiencies, fuel requirements and technical aspects to consider. This taxonomy gives a framework for energy statisticians and analysts for the classification of storage options to expand the understanding of energy systems and the interactions between energy inputs and outputs in short-term energy balances and analyses.

Figure 31 IRENA classification of energy storage



For energy statistics, this classification reflects the need to trace the original fuel sources for each energy carrier, such as fluids, electricity and chemicals. Additionally, it is important to keep track of the energy storage capacity in power units (*e.g.* megawatts) and energy units (*e.g.* megawatt hours), as well as maintain an understanding of storage rates (*i.e.* charging, discharging), lifetime (*i.e.* number of charging cycles), energy density (*i.e.* watt hours per physical unit [*e.g.* litre, kilogramme]), power density (*i.e.* watts per physical unit [*e.g.* litre, kilogramme]), depth of discharge (*e.g.* maximum and optimal), maximum state of charge, charge-discharge response times, and energy cycle efficiencies, including energy charge and discharge ratios.

310000 ELECTRIC STORAGE

Electric storage is an aggregate group dedicated to storing electricity.

311000 Supercapacitors

Supercapacitors are devices that store electricity in the form of electrical charges between two electrodes separated by an electrical insulator and immersed in an electrolyte connecting the electrodes. The theory of supercapacitor storage is similar to electrochemical batteries, but rather than using chemical redox reactions for storage, supercapacitors use electrostatic capacitance.

Supercapacitors or ultracapacitors differ from conventional capacitors due to their fast charge-discharge rates, longer life cycle, high power and high energy density (Sharma and Kumar, 2020). Supercapacitors do not undergo any chemical reaction and can be used for well over 100 000 charging cycles.

Further applications of supercapacitors include their replacement of electrochemical batteries in large vehicles, their co-installation with wind turbines and solar photovoltaic panels, and other backup power applications. However, supercapacitors are not well suited for long-term electricity storage without a significant reduction in their cost (Guerrero *et al.*, 2009).

319000 Other electric storage

Other electric storage options not elsewhere specified.

320000 ELECTROCHEMICAL STORAGE

Electrochemical storage is the storage of electricity in electrochemical cells, colloquially referred to as batteries. These systems convert electrical energy to chemical potential energy through redox reactions. This energy is then reconverted to electricity when required. These cells are mainly composed of four parts: anode (negative electrode), cathode (positive electrode), electrolyte and electrode separator.

This group aggregates different types of electrochemical storage options, based on their mobility.

Box 3 Overview of the lithium-ion battery

Many batteries are categorised today based on their materials. One of the most common types is the lithium-ion cell battery:

A lithium-ion cell usually has an anode made of graphite (carbon), a cathode made of lithium metal oxide, an electrolyte based on lithium salts in an organic solvent, and an electrode separator made of an electrical insulating material (polymer) that creates a barrier between the electrodes but allows the ions to pass through it from one electrode to another.

During charging, the lithium-ion cell works by injecting electricity into the cell, where lithium ions (Li^+) get reduced by the electrons (e^-) and get "stored" in the graphite (C_6) of the anode. At the cathode, the lithium stored in the lithium metal oxide ($LiMO_2$) detaches and is released into the electrolyte as lithium ions, along with electrons. The overall reaction is as follows and goes from left to right during charging of the cell and from right to left during discharging.

Equation 6 Redox reactions of a typical lithium-ion cell

$$C_6 + Li^+ + e^- \longleftrightarrow C_6Li \text{ (anode)}$$

$$LiMO_2 \longleftrightarrow Li_{1-x}MO_2 + xLi^+ + xe^- \text{ (cathode)}$$

One of the challenges of using electrochemical storage is that the cells degrade over time, reducing the capacity of electricity storage. Among the factors that cause cell degradation is the loss of electrolytes through vaporisation and lithium layering onto the graphite anode, degradation of the cathode's structure, and increased resistance due to the anode layering getting bigger after each cycle. Another important consideration in the use of lithium-ion cells is that some elements required to build large-scale electrochemical storage systems depend on critical materials,[a] thus raising concerns about fairness, cost and availability in their production and unavoidable replacement.

[a] *Critical materials are those materials needed to produce energy transition technologies; examples include lithium, nickel, cobalt and copper (IRENA, 2021).*

⊞ 321000 Stationary electric batteries

Stationary electric batteries are electrochemical cells, regardless of their chemistry, that are designed for fixed service locations (*i.e.* not habitually to be moved from place to place) and that are permanently connected to the electricity supply. Common uses for these systems include electricity backup services and short-term electricity storage in centralised or decentralised power generators. Examples include battery fields attached to electricity-generating plants or household batteries for mini-grids in rural areas or installed in households and buildings in urban areas.

⊞ 322000 Mobile electric batteries

Mobile electric batteries are electrochemical cells, regardless of their chemistry, that are mobile. Batteries in electric vehicles are the main example. These batteries have the potential to ease the loads of distribution and transmission grids, particularly for the transport sector.

As the transport sector becomes more electrified, these batteries will become more important to balance grid activity and reduce the need for other pricier and less efficient energy storage options.

329000 Other electrochemical storage

Other electrochemical storage not elsewhere specified.

330000 ELECTROMAGNETIC STORAGE

Electromagnetic storage refers to the storage of energy in the magnetic field of an inductor (Sabihuddin *et al.*, 2015). Electromagnetic storage is usually only available for a short period of time, with the focus being improving the quality of power supply.

This group is an aggregate of energy storage options that employ the electromagnetic field.

331000 Superconducting magnetic storage

Superconducting magnetic storage comprises systems that combine a superconductor, refrigeration, a containment vessel and a power converter to store electricity in a magnetic field (Xue *et al.*, 2006). A magnetic field is generated by direct current electricity flowing through a superconducting coil. The coil is cryogenically cooled to reduce its electrical resistance. The stored electricity can be used by connecting the superconducting coil to an alternating current converter.

⚠ These systems can be designed for large power outputs (megawatt scale) that ease immediate synchronisation issues on the transmission grid.

This category includes all the options to store energy using superconducting magnetic fields, also known as superconducting magnetic energy storage systems.

339000 Other electromagnetic storage

Other electromagnetic storage not elsewhere specified.

340000 MECHANICAL STORAGE

This group includes energy storage options that use mechanical pathways to store energy and may include use of the kinetic energy of fluids or the potential energy of fluids and solids.

341000 Pumped hydro

Pumped hydro is a method of harnessing hydropower potential by pumping water into reservoirs during periods of low electricity demand and releasing it during periods of high demand. Although the energy used to pump water is greater than the energy obtained when it is released, pumped hydro is useful for managing variations in electricity supply and demand.

Traditionally, electrical water pumps powered by the electric grid have been considered non-renewable, but as more countries increase their share of renewable electricity, pumped hydropower has the potential to become renewable. Understanding the energy sources that power the pumps is important for energy statistics.

Capacity statistics include the capacity of all hydropower plants, of any size, that produce hydropower exclusively from pumped hydro. In electricity generation statistics, production from pumped hydro includes all hydropower produced from water previously pumped into hydropower reservoirs. This includes hydropower from pure pumped hydro plants and, for mixed plants, the share of energy produced from pumped hydro. IRENA's energy statistics follow the standards from the Energy Statistics Compilers' Manual (UNSD, 2022) in recording gross electricity generation from pumped hydro, while IRENA excludes this electricity generation from the calculation of total renewable electricity generation. However, this convention should change. As more countries move to renewable electricity generation, the grid electricity used to pump water into storage could be attributed to renewable and non-renewable sources, allowing for an estimated share of the renewable electricity used to pump water. As a result, pumped hydro electricity generation could theoretically be divided between renewable and non-renewable.[14]

342000 Compressed fluids

Compressed fluids use the kinetic energy of pressurised fluids to store energy. In practice, electricity is fed to a fluid compressor that increases the pressure and temperature of a fluid inside a vessel. The pressurised fluid particles have more kinetic energy, bouncing faster inside the vessel until they are channelled through a turbine and then to an electricity generator to produce electricity. Then, the exhausted particles can be returned to the vessel for further cycles of pressurisation.

The thermodynamic conditions for this cycle can vary, resulting in different energy efficiencies for storage but also requiring different design conditions and having different cost implications.

The main example of compressed fluid energy storage is compressed air storage, where electricity powers compressors that increase the pressure of air, pushing it into tanks or underground reservoirs. The compressed air has a larger energy content than air at ambient conditions due to its increased pressure and temperature, and it can then be expanded at a turbine to generate electricity after undergoing additional heating provided by some energy source (commonly by burning natural gas). In terms of thermodynamics, these systems can be operated non-adiabatically, adiabatically or isothermally.

[14] See mixed hydropower (212000) for more information about how electricity statistics are reported. See the Energy Statistics Compilers' Manual (UNSD, 2022) for a more detailed description on how to correctly account for pumped hydro in energy and commodity balances.

These systems could also operate at large enough pressures at low temperatures to store the air as liquid, thus requiring significantly smaller vessels to contain it; such systems are yet to be scaled up into commercial applications (Krawczyk *et al.*, 2018).

Non-adiabatic processes allow the heat from the compression stage to be released into the environment, leading to "cold" compressed air that needs to be reheated when expanded before entering the turbine to avoid freezing and formation of ice. Adiabatic processes thermally isolate the compression of air, thus maintaining high-pressure and high-temperature air inside the vessel. Isothermal processes use heat exchangers during compression to extract the heat of the compressed air and use it elsewhere, thus maintaining the temperature of the air during its compression; this is often accomplished with slow compression of the air.

In principle, compressed fluid storage only works for compressible fluids (*e.g.* water does not work). For gases, compressed storage would largely follow the ideal gas law of $PV = nRT$, where P is pressure, V is volume, n is molar mass, R is the ideal gas constant and T is temperature.

Some research explores using carbon dioxide as the fluid for energy storage, thus serving a double purpose of carbon capture and energy storage. A recent model (Zhang and Wang, 2017) showed an energy storage efficiency of 71% using supercritical carbon dioxide, with an energy density of 23 kWh/m^3. Others (Liu *et al.*, 2020) argue for an efficiency of 60% and a cost of USD 0.23/kWh.

⊞ 343000 Flywheels

Flywheels are energy storage systems that store kinetic energy in a rotating mass. The mass can be rotated by an electric motor; electricity excess from diverse sources could be used for this purpose (Breeze, 2018). Modern flywheels use a bi-directional converter to power a motor using excess electricity (that could come from the grid) or alternatively, to direct electricity back to the grid from a generator inside the flywheel. In the case where the flywheel is being charged with excess electricity, the motor rotates a flywheel rotor housed inside a vacuumed container, converting electricity into kinetic energy, increasing the centripetal speed of the rotor. Then, when the electricity is needed, the sped up flywheel rotor turns an electricity generator, converting its kinetic energy back to electricity (Amiryar and Pullen, 2017).

The energy stored in flywheels depends on the shape and material of the flywheel's rotor, the moment of inertia and the angular velocity of the rotor.

⊞ 344000 Gravitational storage

Gravitational storage uses energy to increase the relative height of solid mass through hydraulic fluids and thus increase the potential energy of the mass, given its increased relative height. Because the potential energy of the mass is a product of the relative height difference, the gravitational force constant, and the weight of the mass, the heavier the mass and the higher it can be raised, the more energy can be stored. When the energy is needed, the solid mass is decreased to its baseline height while pushing the hydraulic fluid to a turbine, generating electricity.

349000 Other mechanical storage

Other mechanical storage not elsewhere specified.

350000 THERMAL STORAGE

Thermal storage refers to technologies that store thermal energy by heating or cooling storage mediums (materials, fluids, *etc.*), whereby the thermal energy can be used later either as heat or transformed into other types of energy, such as electrical energy.

This aggregate group thermal energy storage options that use primarily latent heat (phase changing) or sensible heat (temperature changing) options.

351000 Latent heat storage

Latent heat storage uses energy to heat a fluid or solid to a different physical state (from solid to liquid or gas, or from liquid to gas) using heat exchangers. When the energy is needed, these liquids or gases are returned to their initial physical phase by transferring heat to a colder working fluid. Latent heat is more effective at storing energy than sensible heat since, generally, it takes more energy to change physical phases at a same temperature than to raise the temperature of a substance without changing physical phases.

The amount of heat (Q) being transferred depends on the amount of mass (m) changing phases, and the specific latent heat of a substance (ΔH).

Equation 7 Latent heat transfer equation

$$Q = m\Delta H$$

Different substances have different specific latent heat values. Water is a common choice for thermodynamics in phase changes because of its relatively large specific latent heat value compared with many other substances.

352000 Sensible heat storage

Sensible heat storage comprises systems that use energy to heat a fluid or a solid to a higher temperature using heat exchangers and then keep the fluid or solid under thermally insulated conditions. When energy is needed, the heated fluids or solids transfer heat to a colder working fluid. This is particularly useful for heat end uses.

Sensible heat transfer (Q) depends on the amount of mass (m) being heated or cooled, the specific heat (C) of the substance and the change in temperature (ΔT):

Equation 8 Sensible heat transfer equation

$$Q = mC\Delta T$$

As such, the selection of substance for temperature change can significantly affect the amount of heat that can be transferred. Because of thermal losses to the environment, the substance should be stored in an insulating vessel or material to preserve the heat within it. Many concentrated solar power plants use this option as storage, where the sun heats molten salts inside an isolated vessel. These molten salts can in turn be used during the night to produce steam through a heat exchanger. The steam turns a turbine connected to an electricity generator. Thermal efficiency can range from 50% to 90% depending on the technological choice and thermodynamics of the heat exchange process (Zablocki, 2019).

359000 Other thermal storage

Other thermal storage options not elsewhere specified.

360000 CHEMICAL FUELS STORAGE

Chemical fuels storage is an aggregate group that includes storage as chemicals, particularly those from renewable sources.

361000 Hydrogen storage

Hydrogen storage refers to hydrogen that is stored for energy uses. This hydrogen can come from either renewable or non-renewable sources, as classified in previous categories. At 120 MJ/kg (Rusman and Dahari, 2016),[15] hydrogen is more energy dense by weight than other fuel sources but it is not as volume dense, making its storage a critical aspect of its feasibility as an energy source in economic, technical and safety terms.

This challenge raises questions about the best way to store hydrogen as a fuel to use in different periods, ranging from seconds to months, of its synthesis. While still an emerging topic, hydrogen can be stored via different methods, including compressed gas storage, liquid hydrogen storage and solid hydrogen storage (Tang *et al.*, 2023).

361100 Gas hydrogen storage

There are two common ways to physically store hydrogen gas under pressurised conditions without chemically modifying the hydrogen: in gas containers and in underground reservoirs.

[15] *Considering its lower heating value or net calorific value.*

Gas containers are typically steel alloy cylinders that can keep hydrogen at a pressure of up to 700 bar, raising its volumetric density to around 36 kg/m^3 (Yue *et al.*, 2021). This option is practical for small quantities, but it also has technical complexities, like the heating of the hydrogen and therefore the tanks when decompressing, or the transportation limitations due to the weight of the compressed hydrogen and the tanks containing it. Moreover, hydrogen is the smallest element in the universe, and specialised alloys are required to store it without it permeating through, as it would with traditional steel containers (Gorman and Nardella, 1962), thus posing a combustion and possibly an explosion risk in storage areas. Additionally, special attention is needed to address hydrogen gas leakage, since hydrogen has a high (short- to mid-term) global warming potential that can also perturb the distributions of atmospheric methane and ozone (Ocko and Hamburg, 2022).

Underground reservoirs, such as depleted salt mines, aquifers, or oil and gas deposits, provide a longer-term solution for compressed gas storage of hydrogen. These reservoirs are commonly considered as feasible options for large-scale hydrogen storage under different models (Neumann *et al.*, 2023; Shirizadeh and Quirion, 2023). Underground reservoirs also have a few technical difficulties and geological and environmental concerns that need to be considered. For instance, many require another injection of gas to maintain pressure in the reservoir.

361200 Liquid hydrogen storage

Liquid hydrogen storage refers to hydrogen that is being stored in liquid state, usually in cryogenic tanks (Rusman and Dahari, 2016). At ambient pressure, hydrogen becomes liquid at temperatures close to absolute zero (around 20 K).

This option is attractive for hydrogen because it increases its volumetric density to around 71 kg/m^3 (twice as much as compressed gas) and does not have the high-pressure risks of pressurised gas containers. But because of the large energy demand to liquify hydrogen, this option at current technologies reflects energy transformation losses of around 40% of the hydrogen's energy content at ambient conditions (Yue *et al.*, 2021). As such, this option has mostly been reserved for specialised purposes like space travel (Colozza and Kohout, 2002). Other methods combine low temperatures with high pressure; this is known as cryo-compressed storage (Rusman and Dahari, 2016).

Hydrogen can also be stored in liquid form through covalent bond forming with liquid organic hydrogen carriers such as methylcyclohexane toluene, various cycloalkanes and ammonia-borane-based systems (Teichmann *et al.*, 2012). The hydrogen can be released through dehydrogenation, leaving the liquid organic hydrogen carrier for future storage cycles (Rusman and Dahari, 2016). This is a costly option and technically challenging due to its high-temperature, high-pressure and catalytic requirements (Hu *et al.*, 2015).

⊞ 361300 Solid hydrogen storage

Solid hydrogen storage refers to the storage of hydrogen in solid materials, mostly through the processes of absorption and adsorption. In this category are metal hydrides and adsorbents (Yue *et al.*, 2021). This option is safer than traditional pressurised gas storage, but because of the metal requirements, it becomes a heavier choice that poses logistical transportation challenges.

⊞ 361310 Metal hydride hydrogen storage

Metal hydride hydrogen storage refers to the chemical storage of hydrogen in metal hydrides, often through absorption. At low temperatures, some metals react with hydrogen to form reversible solid metal-hydrogen compounds (Blackman *et al.*, 2006), essentially capturing hydrogen molecules in the metal structures. There is ongoing research to solve some issues related to metal hydrides, such as slow reaction kinetics, low reversibility and high dehydrogenation temperatures (Ma *et al.*, 2013; Principi *et al.*, 2009).

Common metal hydrides for hydrogen storage include magnesium-based hydrides and intermetallic compounds with hydrogen storage capacities ranging from 1.5% to 3% in weight (Rusman and Dahari, 2016).

⊞ 361320 Adsorbent hydrogen storage

Adsorbent hydrogen storage is the storage of hydrogen in solid materials, typically nano-engineered to optimise the adsorption of hydrogen, which could include carbon nanotubes and metal organic frameworks (Rusman and Dahari, 2016). The amount of hydrogen stored often depends on the pressure applied when injecting it onto these materials, but it is typically lower than pressurised hydrogen gas storage.

⊞ 361390 Other solid hydrogen storage

Other solid hydrogen storage not elsewhere specified.

362000 Ammonia storage

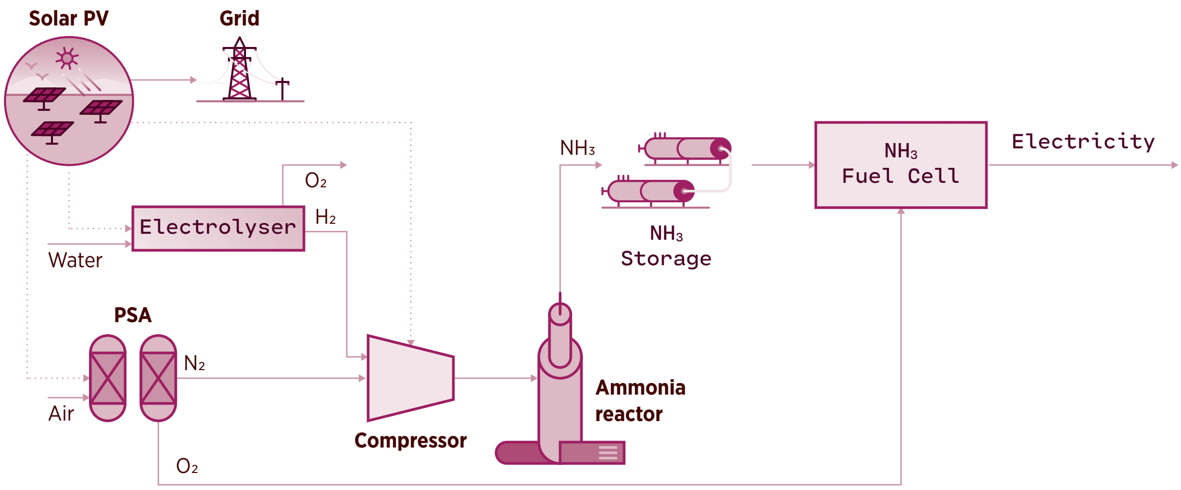
Ammonia storage refers to the use of ammonia to store energy for later use. Given the significant increase in the importance of variable renewable electricity, along with renewable hydrogen, and there being hydrogen and atmospheric air precursors in the synthesis of ammonia, this chemical has the potential to store large amounts of energy coming from renewable sources. Ammonia is also one of the most produced chemicals in the world with one of the longest manufacturing and storage experiences in industry, adding to its techno-economic attractiveness.

Ammonia as storage is also interesting for efficiency purposes, since there are no side reactions involved in the synthesis and decomposition of ammonia (Dunn *et al.*, 2012).

The two most common ammonia storage processes are thermochemical and electrochemical. The thermochemical classification uses high-temperature heat from concentrated solar power to decompose ammonia, while generating power through the exothermic reaction of ammonia synthesis. The electrochemical classification uses hydrogen to synthesise ammonia and then uses this ammonia to generate electricity in a fuel cell.

Figure 32 showcases the electrochemical pathway for ammonia storage.

Figure 32 Process for ammonia energy storage without cooling



Based on: Tawalbeh et al., 2022
Notes: H_2 = hydrogen; N_2 = nitrogen; NH_3 = Ammonia; O_2 = oxygen; PSA = pressure swing adsorption.

369000 Other chemical fuels storage

Other chemical fuels storage not elsewhere specified.

SPECIAL GROUPINGS

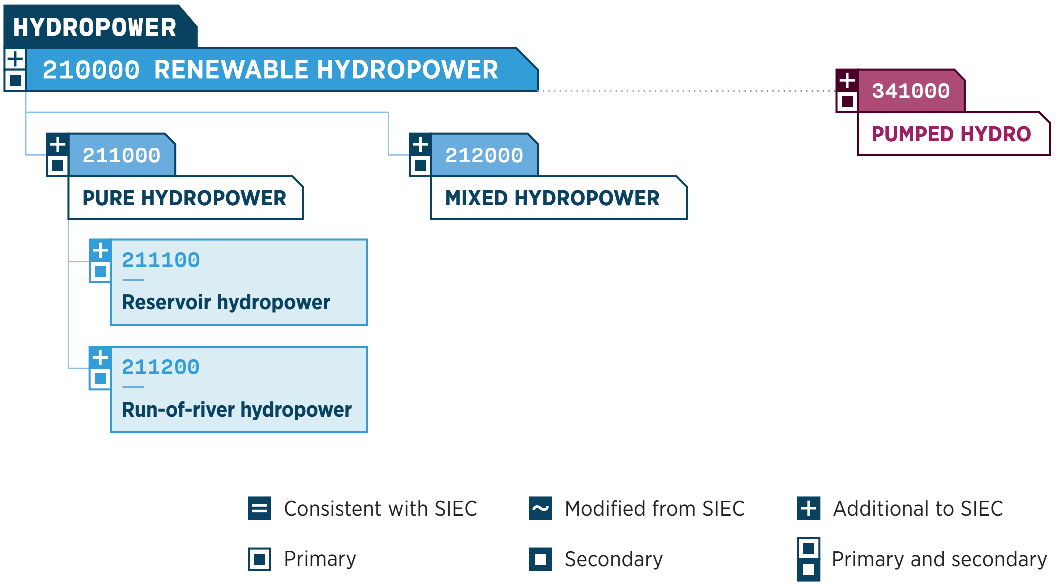
In some cases, it is more relevant for analytical purposes to have special groupings that do not follow this taxonomy's first-level division renewables/non-renewables. This section displays several special groupings that might be of interest for decision makers, analysts and thought leaders.

For example, when looking at electricity generation by energy source, it might be relevant to aggregate all the electricity generated by hydropower, including pumped hydro. As such, the aggregation of electricity would not follow the renewable/non-renewable division and would merge them instead.

In other cases, quantifying the mass production of hydrogen helps build understanding of the supply and demand dynamics or of international trade trends or scenarios. For that, it would be necessary to merge the renewable/non-renewable nature of hydrogen production as well as its use as an energy storage chemical.

HYDROPOWER

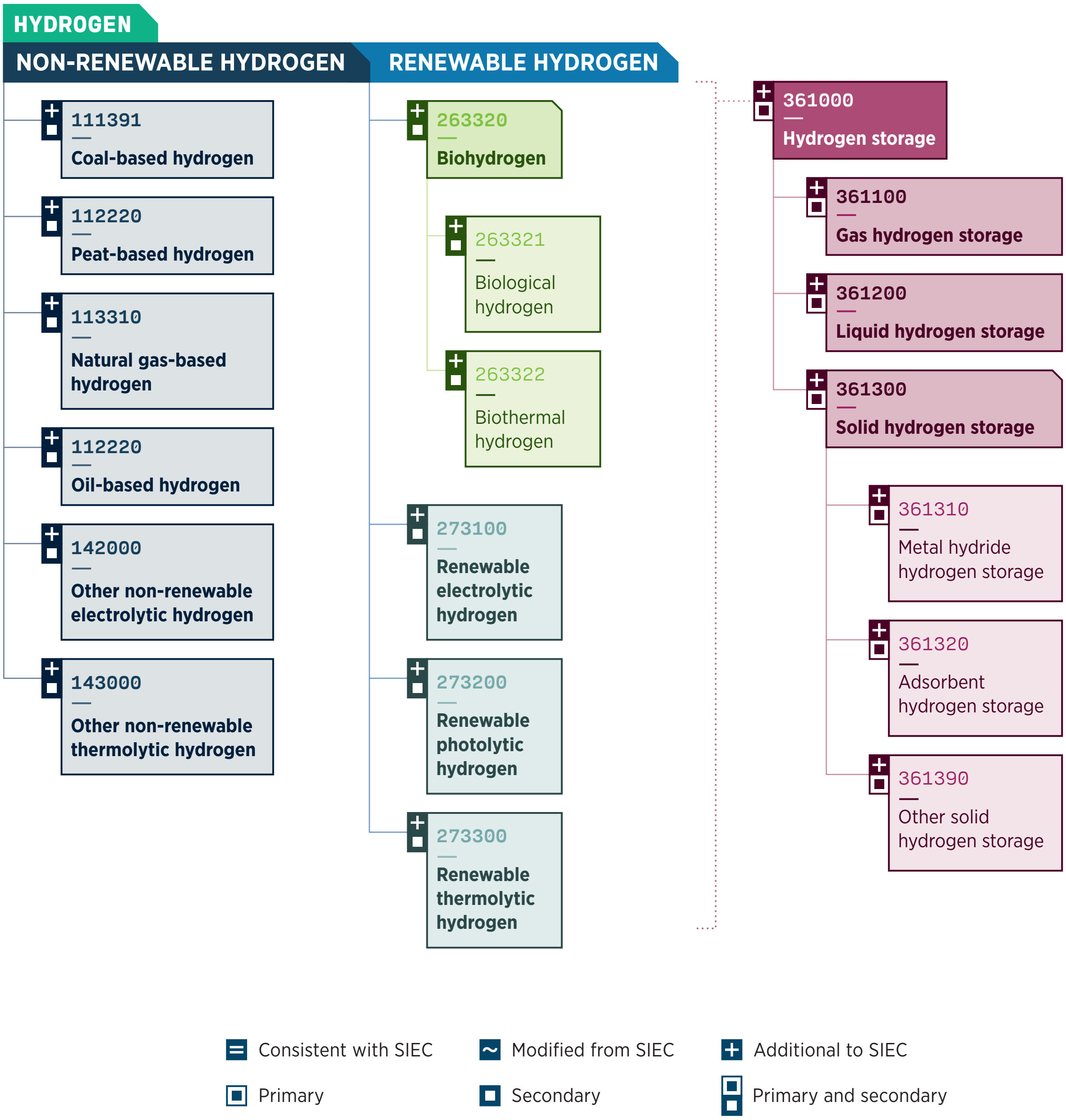
Figure 33 Special grouping for hydropower



The special grouping for hydropower combines storage with renewable energy. This is a crucial distinction for energy statistics that changes the overall percentage of renewable energy in a power system, both in terms of installed capacity and in terms of electricity generation.

HYDROGEN

Figure 34 Special grouping for hydrogen



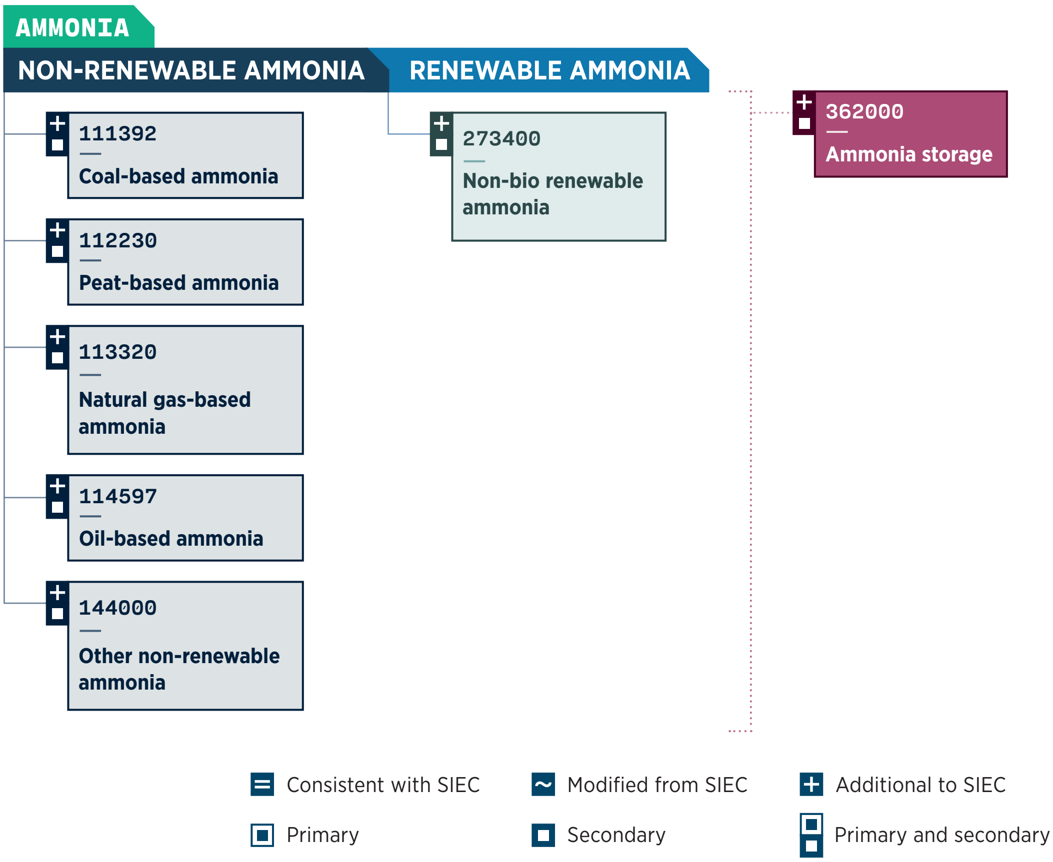
In IRENA's taxonomy, hydrogen can be produced from multiple sources. The best known are natural gas-based hydrogen and renewable electrolytic hydrogen.

Ideally, hydrogen would have an identifiable energy source. In that case, hydrogen storage could be attributed to specific hydrogen sources. But if hydrogen storage is a mix of different hydrogen sources or there is no detailed information, a statistical simplification is to consider hydrogen storage as its own separate category (as shown in Figure 34).

In this special grouping, electrolytic, photolytic and thermolytic hydrogen are not categorised under a specific renewable energy, since the raw energy used to produce them is the intermediary electricity, so instead they are categorised under renewable electrolytic, photolytic or thermolytic hydrogen and non-renewable electrolytic or thermolytic hydrogen. This simplifies statistics and allows for a one-to-one comparison in physical terms with other kinds of hydrogen energy or material sources. Special attention is needed in an energy balance to account for hydrogen as a secondary commodity for electrolytic, photolytic, and thermolytic hydrogen, products of transformation from one or multiple primary energy sources.

AMMONIA

Figure 35 Special grouping for ammonia



The classification of ammonia is further simplified compared with that of hydrogen: non-renewable ammonia can be attributed to its hydrocarbon source and renewable ammonia is inclusive of all the pathways to produce ammonia using renewable energy or materials. In energy statistics, accounting for renewable ammonia should be straightforward as a tertiary product from renewable hydrogen.

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APPENDIX A.
TAXONOMY TABLE

The table below summarises the entire taxonomy.

Table 4 Energy taxonomy

TechCode	Technology	Parent	Energy type
900000	**Energy**		**Total energy**
100000	**Non-renewable energy**	**900000**	**Non-renewable**
110000	**Fossil fuels**	**100000**	**Non-renewable**
111000	**Coal**	**110000**	**Non-renewable**
111100	**Hard coal**	**111000**	**Non-renewable**
111110	Anthracite	111100	Non-renewable
111120	Bituminous coal	111100	Non-renewable
111121	Coking coal	111120	Non-renewable
111129	Other bituminous coal	111120	Non-renewable
111200	**Brown coal**	**111000**	**Non-renewable**
111210	Sub-bituminous coal	111200	Non-renewable
111220	Lignite	111200	Non-renewable
111300	**Coal products**	**111000**	**Non-renewable**
111310	Coal coke	111300	Non-renewable
111311	Coke oven coke	111310	Non-renewable
111312	Gas coke	111310	Non-renewable
111313	Coke breeze	111310	Non-renewable
111314	Semi cokes	111310	Non-renewable
111320	Patent fuel	111300	Non-renewable
111330	Brown coal briquettes	111300	Non-renewable
111340	Coal tar	111300	Non-renewable
111350	Coke oven gas	111300	Non-renewable
111360	Gas works gas	111300	Non-renewable
111370	Recovered gases	111300	Non-renewable
111371	Blast furnace gas	111370	Non-renewable
111372	Basic oxygen steel furnace gas	111370	Non-renewable
111373	Other recovered gases	111370	Non-renewable
111390	Other coal products	111300	Non-renewable
111391	Coal-based hydrogen	111390	Non-renewable
111392	Coal-based ammonia	111390	Non-renewable
111399	Other coal products n.e.s.	111390	Non-renewable

TechCode	Technology	Parent	Energy type
112000	**Peat and peat products**	**110000**	**Non-renewable**
112100	**Peat**	**112000**	**Non-renewable**
112110	Sod peat	112100	Non-renewable
112120	Milled peat	112100	Non-renewable
112200	**Peat products**	**112000**	**Non-renewable**
112210	Peat briquettes	112200	Non-renewable
112220	Peat-based hydrogen	112200	Non-renewable
112230	Peat-based ammonia	112200	Non-renewable
112290	Other peat products	112200	Non-renewable
113000	**Natural gas**	**110000**	**Non-renewable**
113100	**Wet natural gas**	**113000**	**Non-renewable**
113200	**Dry natural gas**	**113000**	**Non-renewable**
113210	Liquefied natural gas	113200	Non-renewable
113220	Compressed natural gas	113200	Non-renewable
113300	**Natural gas products**	**113000**	**Non-renewable**
113310	Natural gas-based hydrogen	113300	Non-renewable
113320	Natural gas-based ammonia	113300	Non-renewable
113390	Other natural gas products	113300	Non-renewable
114000	**Oil**	**110000**	**Non-renewable**
114100	**Conventional crude oil**	**114000**	**Non-renewable**
114200	**Natural gas liquids**	**114000**	**Non-renewable**
114300	**Refinery feedstocks**	**114000**	**Non-renewable**
114400	**Additives and oxygenates**	**114000**	**Non-renewable**
114500	**Oil products**	**114000**	**Non-renewable**
114510	Refinery gas	114500	Non-renewable
114520	Ethane	114500	Non-renewable
114530	Liquefied petroleum gases	114500	Non-renewable
114540	Naphtha	114500	Non-renewable
114550	Gasolines	114500	Non-renewable
114551	Aviation gasoline	114550	Non-renewable
114552	Motor gasoline	114550	Non-renewable
114553	Gasoline-type jet fuel	114550	Non-renewable
114560	Kerosenes	114500	Non-renewable
114561	Kerosene-type jet fuel	114560	Non-renewable
114569	Other kerosene	114560	Non-renewable
114570	Gas oil/diesel oil and heavy gas oil	114500	Non-renewable
114571	Gas oil/diesel oil	114570	Non-renewable
114572	Heavy gas oil	114570	Non-renewable
114580	Fuel oil	114500	Non-renewable

TechCode	Technology	Parent	Energy type
114590	Other oil products	114500	Non-renewable
114591	White spirit	114590	Non-renewable
114592	Lubricants	114590	Non-renewable
114593	Paraffin waxes	114590	Non-renewable
114594	Petroleum coke	114590	Non-renewable
114595	Bitumen	114590	Non-renewable
114596	Oil-based hydrogen	114590	Non-renewable
114597	Oil-based ammonia	114590	Non-renewable
114599	Other oil products n.e.s.	114590	Non-renewable
115000	**Oil shale/sands**	**110000**	**Non-renewable**
119000	**Other fossil fuels**	**110000**	**Non-renewable**
119100	**Other primary fossil fuels**	**119000**	**Non-renewable**
119200	**Other fossil fuel products**	**119000**	**Non-renewable**
119900	**Other fossil fuels n.e.s.**	**119000**	**Non-renewable**
120000	**Nuclear energy**	**100000**	**Non-renewable**
121000	**Uranium and plutonium**	**120000**	**Non-renewable**
122000	**Nuclear fusion fuels**	**120000**	**Non-renewable**
129000	**Other nuclear fuels**	**120000**	**Non-renewable**
130000	**Non-renewable waste**	**100000**	**Non-renewable**
131000	**Non-renewable industrial waste**	**130000**	**Non-renewable**
132000	**Non-renewable municipal waste**	**130000**	**Non-renewable**
140000	**Other non-renewable energy**	**100000**	**Non-renewable**
141000	**Chemical heat**	**140000**	**Non-renewable**
142000	**Other non-renewable electrolytic hydrogen**	**140000**	**Non-renewable**
143000	**Other non-renewable thermolytic hydrogen**	**140000**	**Non-renewable**
144000	**Other non-renewable ammonia**	**140000**	**Non-renewable**
149000	**Other non-renewable energy n.e.s.**	**140000**	**Non-renewable**
200000	**Renewable energy**	**900000**	**Renewables**
210000	**Renewable hydropower**	**200000**	**Renewables**
211000	**Pure hydropower**	**210000**	**Renewables**
211100	**Reservoir hydropower**	**211000**	**Renewables**
211200	**Run-of-river hydropower**	**211000**	**Renewables**
212000	**Mixed hydropower**	**210000**	**Renewables**
220000	**Marine energy**	**200000**	**Renewables**
221000	**Wave energy**	**220000**	**Renewables**
222000	**Tidal energy**	**220000**	**Renewables**
223000	**Ocean current**	**220000**	**Renewables**
224000	**Salinity gradient**	**220000**	**Renewables**
225000	**Thermal gradient**	**220000**	**Renewables**

TechCode	Technology	Parent	Energy type
230000	**Wind energy**	**200000**	**Renewables**
231000	**Onshore wind energy**	**230000**	**Renewables**
232000	**Offshore wind energy**	**230000**	**Renewables**
240000	**Solar energy**	**200000**	**Renewables**
241000	**Solar photovoltaic**	**240000**	**Renewables**
241100	**On-grid solar photovoltaic**	**241000**	**Renewables**
241110	On-grid utility-scale photovoltaic (>1000 kW)	241100	Renewables
241120	On-grid distributed photovoltaic (30-1000 kW)	241100	Renewables
241130	On-grid distributed photovoltaic (<30 kW)	241100	Renewables
241200	**Off-grid solar photovoltaic**	**241000**	**Renewables**
241210	Solar lights	241200	Renewables
241220	Small solar home systems	241200	Renewables
241230	Large solar home systems	241200	Renewables
241240	Solar telecom towers	241200	Renewables
241250	Solar water pumps	241200	Renewables
241260	Solar mini-grids	241200	Renewables
241270	Solar street lamps	241200	Renewables
241290	Other off-grid solar photovoltaic	241200	Renewables
242000	**Solar thermal energy**	**240000**	**Renewables**
242100	**Concentrated solar power**	**242000**	**Renewables**
242110	Heliostat field collector	242100	Renewables
242120	Linear Fresnel reflector	242100	Renewables
242130	Parabolic dish	242100	Renewables
242140	Parabolic trough	242100	Renewables
242190	Other concentrated solar power	242100	Renewables
242200	**Solar water heating**	**242000**	**Renewables**
242210	Unglazed solar water heaters	242200	Renewables
242220	Glazed single solar water heaters	242200	Renewables
242230	Glazed combined solar water heaters	242200	Renewables
242240	Concentrated solar water heaters	242200	Renewables
242300	**Solar air heating**	**242000**	**Renewables**
242310	Solar air natural convection heating	242300	Renewables
242320	Solar air forced convection heating	242300	Renewables
242330	Solar air radiative heating	242300	Renewables
242900	**Other solar thermal energy**	**242000**	**Renewables**
250000	**Geothermal energy**	**200000**	**Renewables**
251000	**Geothermal heat and power**	**250000**	**Renewables**
252000	**Direct use of geothermal heat**	**250000**	**Renewables**

TechCode	Technology	Parent	Energy type
260000	**Bioenergy**	**200000**	**Renewables**
261000	**Solid biofuels**	**260000**	**Renewables**
261100	**Harvested biomass**	**261000**	**Renewables**
261110	Wood fuel	261100	Renewables
261120	Energy crops	261100	Renewables
261190	Other harvested biomass	261100	Renewables
261200	**Harvest residues**	**261000**	**Renewables**
261210	Logging residues	261200	Renewables
261220	Straw	261200	Renewables
261290	Other harvest residues	261200	Renewables
261300	**Biomass processing residues**	**261000**	**Renewables**
261310	Bagasse	261300	Renewables
261320	Black liquor	261300	Renewables
261330	Plant husks	261300	Renewables
261340	Plant shells	261300	Renewables
261350	Solid wood processing residues	261300	Renewables
261360	Oil plant residues	261300	Renewables
261390	Other biomass processing residues	261300	Renewables
261400	**Animal residues**	**261000**	**Renewables**
261410	Manure/dung	261400	Renewables
261420	Animal processing residues	261400	Renewables
261490	Other animal residues	261400	Renewables
261500	**Biomass pellets and briquettes**	**261000**	**Renewables**
261510	Wood pellets and briquettes	261500	Renewables
261520	Oil cakes	261500	Renewables
261590	Other biomass pellets and briquettes	261500	Renewables
261600	**Charcoal**	**261000**	**Renewables**
261900	**Other solid biofuels**	**261000**	**Renewables**
262000	**Liquid biofuels**	**260000**	**Renewables**
262100	**Biogasolines**	**262000**	**Renewables**
262110	Biomethanol	262100	Renewables
262120	Bioethanol	262100	Renewables
262130	Biobutanol	262100	Renewables
262140	Bio-MTBE	262100	Renewables
262150	Bio-ETBE	262100	Renewables
262190	Other biogasolines	262100	Renewables
262200	**Biodiesels**	**262000**	**Renewables**
262210	Transesterified biodiesel	262200	Renewables
262220	Thermal process biodiesel	262200	Renewables
262230	Microalgal biodiesel	262200	Renewables

TechCode	Technology	Parent	Energy type
262240	Straight vegetable oil	262200	Renewables
262250	Hydrogenated vegetable oil diesel	262200	Renewables
262290	Other biodiesels	262200	Renewables
262300	**Bio-jet kerosenes**	**262000**	**Renewables**
262900	**Other liquid biofuels**	**262000**	**Renewables**
262910	Bio-LPG	262900	Renewables
262990	Other liquid biofuels n.e.s.	262900	Renewables
263000	**Gas biofuels**	**260000**	**Renewables**
263100	**Biogas from anaerobic digestion**	**263000**	**Renewables**
263110	Landfill biogas	263100	Renewables
263120	Wastewater sludge biogas	263100	Renewables
263130	Animal residue biogas	263100	Renewables
263140	Vegetal residue biogas	263100	Renewables
263190	Other biogas from anaerobic digestion	263100	Renewables
263200	**Biogas from thermal processes**	**263000**	**Renewables**
263300	**Gas biofuels products**	**263000**	**Renewables**
263310	Biomethane	263300	Renewables
263320	Biohydrogen	263300	Renewables
263321	Biological hydrogen	263320	Renewables
263322	Biothermal hydrogen	263320	Renewables
263330	Bio-DME	263300	Renewables
263390	Other gas biofuels products	263300	Renewables
264000	**Renewable waste**	**260000**	**Renewables**
264100	**Renewable municipal waste**	**264000**	**Renewables**
264200	**Renewable industrial waste**	**264000**	**Renewables**
270000	**Non-bio renewable fuels**	**200000**	**Renewables**
271000	**Non-bio renewable solid fuels**	**270000**	**Renewables**
271100	**Non-bio renewable carbon**	**271000**	**Renewables**
271900	**Other non-bio renewable solid fuels**	**271000**	**Renewables**
272000	**Non-bio renewable liquid fuels**	**270000**	**Renewables**
272100	**Non-bio renewable gasolines**	**272000**	**Renewables**
272200	**Non-bio renewable diesels**	**272000**	**Renewables**
272300	**Non-bio renewable kerosenes**	**272000**	**Renewables**
272900	**Other non-bio renewable liquid fuels**	**272000**	**Renewables**
273000	**Non-bio renewable gas fuels**	**270000**	**Renewables**
273100	**Renewable electrolytic hydrogen**	**273000**	**Renewables**
273200	**Renewable photolytic hydrogen**	**273000**	**Renewables**
273300	**Renewable thermolytic hydrogen**	**273000**	**Renewables**
273400	**Non-bio renewable ammonia**	**273000**	**Renewables**
273500	**Non-bio renewable DME**	**273000**	**Renewables**

TechCode	Technology	Parent	Energy type
273600	Non-bio renewable methane	273000	Renewables
273900	Other non-bio renewable gas fuels	273000	Renewables
280000	Multiple renewables	200000	Renewables
290000	Other renewable energy	200000	Renewables
291000	Air-source heat pump	290000	Renewables
292000	Water-source heat pump	290000	Renewables
293000	Ground-source heat pump	290000	Renewables
299000	Other renewable energy n.e.s.	290000	Renewables
300000	Energy storage	900000	Storage
310000	Electric storage	300000	Storage
311000	Supercapacitors	310000	Storage
319000	Other electric storage	310000	Storage
320000	Electrochemical storage	300000	Storage
321000	Stationary electric batteries	320000	Storage
322000	Mobile electric batteries	320000	Storage
329000	Other electrochemical storage	320000	Storage
330000	Electromagnetic storage	300000	Storage
331000	Superconducting magnetic storage	330000	Storage
339000	Other electromagnetic storage	330000	Storage
340000	Mechanical storage	300000	Storage
341000	Pumped hydro	340000	Storage
342000	Compressed fluids	340000	Storage
343000	Flywheels	340000	Storage
344000	Gravitational storage	340000	Storage
349000	Other mechanical storage	340000	Storage
350000	Thermal storage	300000	Storage
351000	Latent heat storage	350000	Storage
352000	Sensible heat storage	350000	Storage
359000	Other thermal storage	350000	Storage
360000	Chemical fuels storage	300000	Storage
361000	Hydrogen storage	360000	Storage
361100	Gas hydrogen storage	361000	Storage
361200	Liquid hydrogen storage	361000	Storage
361300	Solid hydrogen storage	361000	Storage
361310	Metal hydride hydrogen storage	361300	Storage
361320	Adsorbent hydrogen storage	361300	Storage
361390	Other solid hydrogen storage	361300	Storage
362000	Ammonia storage	360000	Storage
369000	Other chemical fuels storage	360000	Storage

APPENDIX B.

TAXONOMY DIAGRAM

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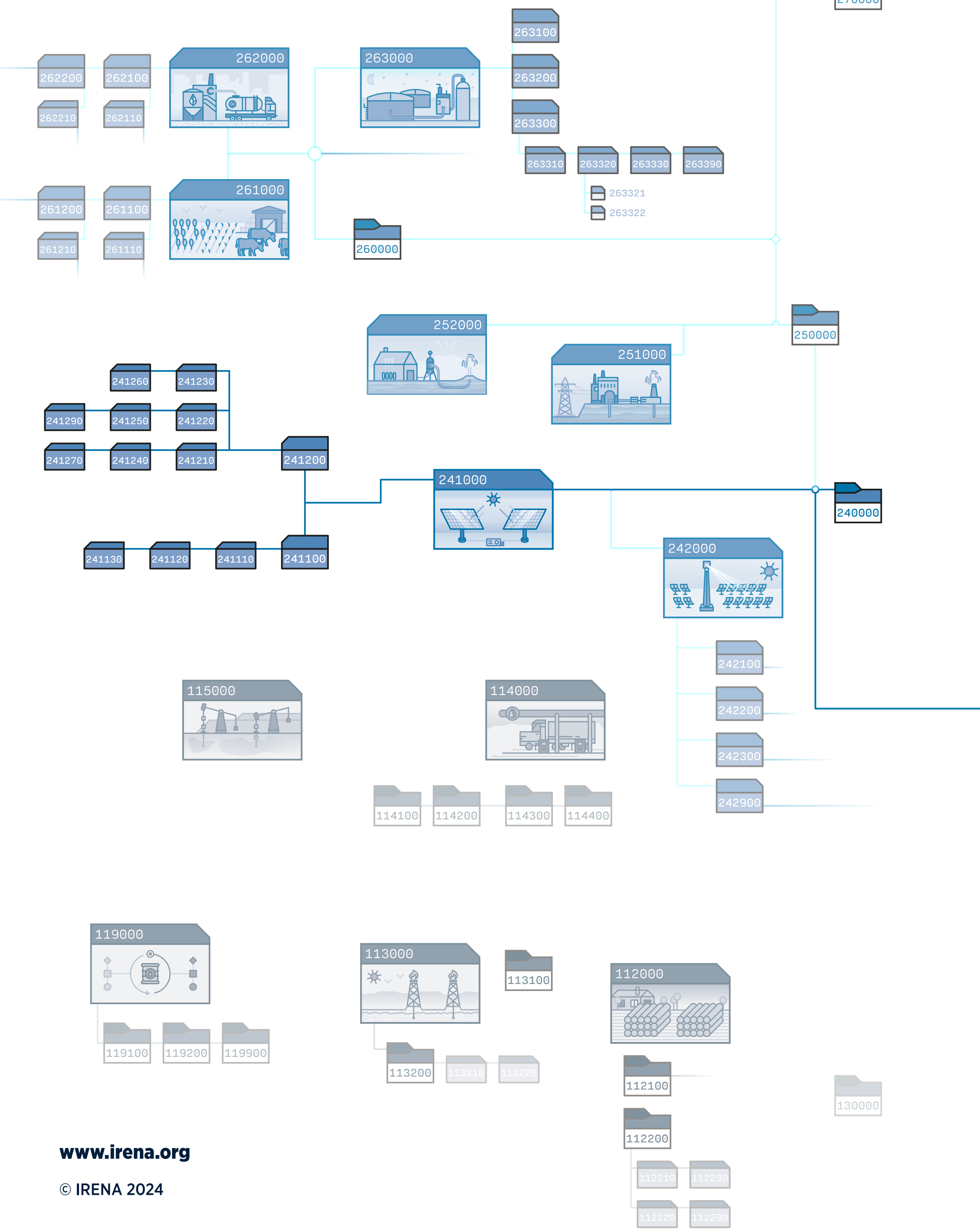
International Renewable Energy Agency



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