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Life Cycle Assessment of a Gas Turbine Installation

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Abstract: Gas turbine installations (GTIs) are widely used to generate electrical and thermal energy mainly by burning gaseous fuels. The use of GTIs to burn hydrogen as part of the development of hydrogen energy technology is currently of particular interest. In order to assess the prospects of using GTIs in such a way, it is necessary, among other things, to understand the carbon footprint of the gas turbine as part of the carbon footprint of the entire life cycle of hydrogen. The article provides an overview of the results of previously published studies on life cycle assessment (LCA) of technically complex devices associated with the production and consumption of fuel and energy, which, from the point of view of the complexity of LCA, are most similar to gas turbine installation. The characteristics of the considered stages and resources used in the assessment of the stages of the life cycle of technically complex equipment are presented, including an analysis of the amount of materials used in production and construction. Taking into account its specific application in Russia, an assessment of greenhouse gas emissions at the stages of the GTI life cycle per MWh of produced capacity was carried out.

Keywords: technically complex device; gas turbine installation; carbon footprint; life cycle assessment

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1. Introduction

The use of a clean, reliable and relatively inexpensive source of energy is of current importance. Today, there is active development and research in the field of hydrogen energy, since hydrogen is a fuel that does not produce greenhouse gases when burned, and inexhaustible resources (e.g. water and solar energy) can be used to produce it. The relevance of using hydrogen as a fuel is due to the limited hydrocarbon energy sources, the negative environmental impact of traditional fuels and the unsatisfactory efficiency of "green" energy. Unfortunately, most of the hydrogen currently produced belongs to the "grey" category - its production is accompanied by significant consumption of electricity derived from fossil fuels (steam methane reforming, coal gasification) and CO_2 emissions [1].

Hydrogen is a promising energy resource from the point of view of industrial decarbonisation and can be used in energy carriers such as fuel cells, internal combustion engines and gas turbines, hydrogen power plants for transport and energy. However, in order to achieve the expected effect of using hydrogen, it is necessary to reliably determine its carbon footprint over its entire life cycle, from the extraction of raw materials to its final use, taking into account the consumption of basic resources (electricity, heat, water consumption, etc.). The application of Life Cycle Assessment (LCA) methodology, which has to be adapted to the specificities of each case, can successfully solve this problem.

When assessing the carbon footprint of fuel use in power plants, the life cycle chains of both the fuel itself and the power plants need to be taken into account. The carbon footprint of the fuel itself (especially fossil and hydrogen fuels) is often incomparably larger than the contribution of the fuel-using equipment (internal combustion engines, gas turbines and combined cycle plants, etc.) to greenhouse gas emissions per unit of energy received or work performed. However, the assessment

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of the carbon footprint of installations is necessary for understanding the contribution to the total greenhouse gas emissions, as well as for comparing alternative energy installations with each other and with the installations that do not use fuels for energy production (solar panels and wind turbines).

One of the most promising alternatives for the use of hydrogen is currently a gas turbine plant. The main advantage of using hydrogen in electricity production with the help of gas turbines is the significantly lower greenhouse gas emissions. The most widely used are low power gas turbine plants (from 2.5 to 25 MW), which are made by converting aeroderivative gas turbine engines (GTE). The use of gas turbines in power generation, industry and transport is promising due to their higher energy efficiency, compactness and low weight compared to other types of power plants [2].

The most widespread use of gas turbines in the power industry is to drive electrical generators, which are used as part of simple cycle gas turbine power plants (SCTGP) and combined cycle gas turbine (CCGT) condensing power plants, which produce "clean" electricity, and as part of combined heat and power plants, which produce both electrical and thermal energy. [3]. A gas turbine plant can be installed in companies as a main, additional or backup source of electricity. The main advantages of gas turbine installation are: low cost of produced heat and electricity, significant reduction of electrical and thermal energy losses due to their proximity to consumers, autonomous operation, possibility of quick construction, low fuel consumption, etc.

Most of the existing gas turbine plants, without changing their design, can operate on a fuel mixture with a hydrogen content of up to 20%, which makes it possible to increase the efficiency of gas utilisation by 20-25%, reduce fuel consumption by up to 35%, while at the same time reducing NOx emissions by a factor of 4 and CO_2 and CO emissions by a factor of 1.5 [4,5]. Serial manufacturers of gas turbines such as GE Gas Power, Baker Hughes, Siemens Energy, Mitsubishi Power, Ansaldo Energia, Kawasaki Heavy Industries, etc. confirm the operation of gas turbines on fuel gas mixtures with H_2 content up to 20% [6]. Ansaldo Energia is carrying out a series of works on existing gas turbine plants to modify the combustion chamber and partially replace a number of materials used to use up to 40% hydrogen in the fuel. New gas turbine plants are equipped with two-zone low-emission combustion chambers (LECC), which allow the combustion of gas mixtures with a 50% hydrogen content [7]. General Electric produces conversion gas turbines (LM2500 with an output of 22 MW, based on CF6-6) that can operate on hydrogen-containing fuels with a hydrogen content of up to 85%. [8]. In 2020, Siemens Energy will test conversion gas turbines capable of running on up to 100% hydrogen (SGT-A35, 35 MW capacity) [9].

Today, gas turbines have great potential for electricity generation compared to solid oxide fuel cells (SOFCs). SOFCs are limited in their output power (up to 100 kW) [10], have high fuel quality requirements, the start-up speed of a fuel cell is several times lower than that of a gas turbine plant [11], and they have a high cost per kW of energy produced - $1875 (SOFC with a power of 5 kW) and $1215 (SOFC with a power of 10 kW), etc. [12].

In most of the studies dealing with LCA of GTI and GTI as a part of combined cycle power plants with CCSPPs [13–19], the equipment is divided into 4-8 materials, material processing technologies in the production of equipment components are not taken into account, as well as transportation of materials (parts) and structures, maintenance and repair of the equipment during the operation phase.

It is quite difficult to assess the carbon footprint of GTIs due to the use of a large number of materials for production, multi-stage technology for their processing, long-term technology for the development of GTI components, etc. A gas turbine plant is a technically complex device and it is extremely difficult to carry out LCA at all stages due to a number of reasons mentioned above, therefore it is necessary to introduce limitations and assumptions. However, it is necessary to identify which stages (processes, materials, resources, etc.) should or should not be included in the LCA.

This was done by analysing the LCA results of other technically complex equipment. As analogues to GTIs, technically complex devices were selected for the LCA, which are structurally similar installations (turbines), fuel-using and "fuel-free" installations for electricity generation. To date, a number of studies have been published on the LCA of technically complex equipment: wind

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turbines [13,20–28], electric vehicles [29,30], buses [13], power plants [31], aircraft [13,32,33], aircraft engines [34], gas turbines and combined cycle power plants [13–19].

Taking into account the results of the analyses carried out, an approach to assess the life cycle of a gas turbine plant was justified and an environmental impact analysis was carried out based on the size of the carbon footprint.

2. Materials and Methods

2.1. General Principles of LCA

LCA is a methodological framework for analysing and evaluating the environmental impacts associated with a product's life cycle, including raw material extraction, manufacturing, distribution, transportation and end-of-life disposal.

At the Life Cycle Inventory analysis stage, the data collected on the quantities of resources consumed (e.g. metals, electricity, etc.) are first converted into elementary flows. At the impact assessment stage, the elementary flows are further converted into environmental impact indicators. This means that the contribution of individual substances to a particular impact is taken into account. Primary data obtained by direct measurement (inventory data of the main processes - quantities of fuels and materials) or calculations based on direct measurement, and secondary data obtained by any other method than primary data (e.g. data on electricity consumed in the production of the material) can be used as data for the LCA.

The inventory analysis was carried out using open data published in scientific articles, books, electronic resources and the electronic database Ecoinvent 3.8 (Ecoinvent Association, Switzerland). The LCA was performed using OpenLCA 1.10.3 software for LCA of products and materials (GreenDelta GmbH, Germany).

2.2. Functional Unit

The functional unit for energy generating equipment or engines, including those that consume fuel, is a unit of energy produced, and in the case of electricity and/or heat production (kWh, MW) [13–18,20–28,31] or work performed - a kilometre of car travel [29,30], a passenger kilometre (PKM) of air travel [32,33], etc.

To estimate the carbon footprint of fuel consuming equipment, the carbon footprint of the fuel is often taken into account. As a functional unit for fuel, mass values are used - kg CO_2-eq./t, kg CO_2-eq./m^3, or taking into account the heat of the fuel combustion – kg CO_2-eq./MJ.

When assessing the carbon footprint of technically complex devices, the following functional units are used: for wind turbines - g CO_2-eq./kW [20,25], kg CO2-eq./kW [23], t CO_2-eq./MW [24], for power generating plants and combined cycle power plants - kg CO_2-eq./kW*h [15,16], g CO_2-eq./kW*h [17], kg CO_2-eq./GW [14], for cars - g CO_2 –eq./km [29,30], etc. Based on the analysis of the research papers, g CO_2-eq./kW*h is taken as the functional unit for assessing the carbon footprint of a land-based gas turbine installation used for electricity generation.

2.3. Limits of LCA

The definition of system boundaries plays an important role in the LCA process, as incorrectly chosen system boundaries can significantly affect the results of the assessment. Traditionally, LCA should start with the extraction of raw materials and end with the disposal of the components. Within the considered system boundaries the main production process can be subdivided into additional processes depending on the level of detail.

The life cycles of fuels and fuel-consuming equipment intersect at the stage of equipment operation in the form of energy received or work performed, which together contribute to the carbon footprint (Figure 1).

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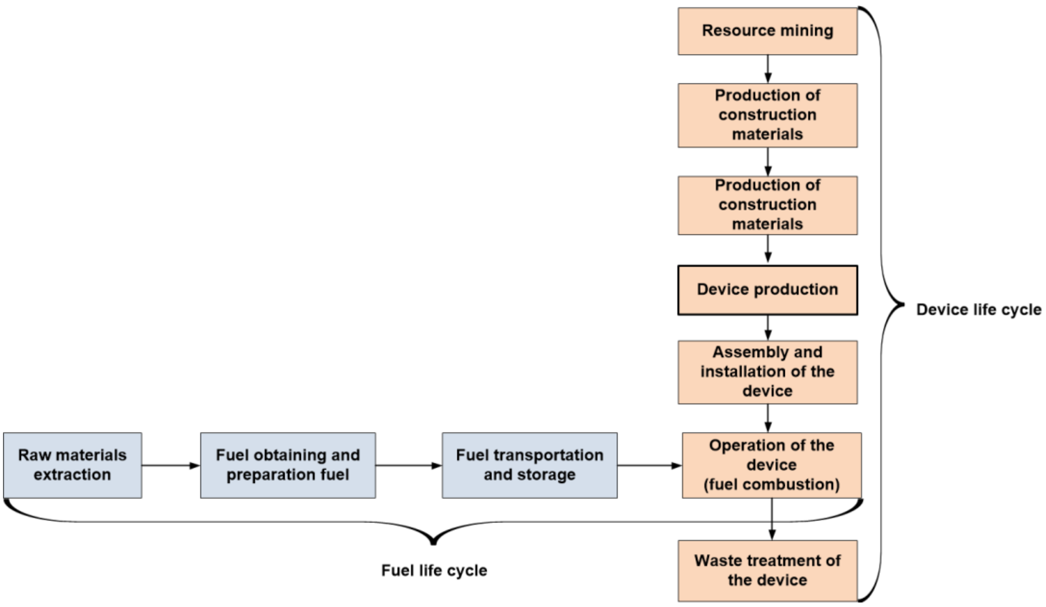

Figure 1. Life cycle of fuel/energy and fuel-consuming device.

In the case of electricity generation, for example, research [18] has shown that 410 g CO_2-eq./kW*h are associated with the life cycle of the fuel (natural gas) and 1.1 g CO_2-eq./kW*h with the life cycle of the combustion plant (gas turbine power plant). For technically complex equipment such as wind turbines and solar panels, the carbon footprint of the electricity they generate is only determined by the life cycle of the equipment itself (energy sources - the sun or the wind - do not have a carbon footprint). When assessing the life cycle of a gas turbine plant, the life cycle of the fuel (hydrogen) is not taken into account.

When performing an LCA of a technically complex product such as a gas turbine, the following stages need to be considered:

- The production stage, which includes the processes of obtaining structural materials, their processing, production of components, assembly and installation; production of operating materials and spare parts.
- The stage of producing fuel and electrical energy.
- The operational stage, which includes the use of the device in the field, maintenance and repair procedures, including the replacement of failed components.
- The disposal stage, including the processes of decomposition, processing (recycling) of materials and disposal of waste at the end of its useful life.

Examples of the coverage of individual stages and processes in LCA studies of technically complex products are shown in Table S1.

The analysis of the LCA studies of technically complex equipment has allowed the identification of the parameters considered at each stage of the life cycle.

The LCA of wind turbines compared to other technically complex equipment is considered in more detail. At the production stage of wind turbines, the materials used are divided according to the main elements produced: nacelle, rotor, blades, tower and mooring system (for offshore turbines) [13,20–24,27]. Among the types of material processing, the following are considered: injection moulding for composite materials in the manufacture of rotors, rolling (steel, aluminium), welding and copper wire drawing [13]. In the research work [25], when a category such as steel is chosen for the LCA in the SimaPro programme, the steel production processes take into account the extraction and production of raw materials depending on the type (low alloy, chrome, etc.). The foundation, electronics, substation and electrical cabling were considered as auxiliary structures [13,22–29]. Other resources included lubricating oil [21–23,27], paints, varnishes [13,23,25], adhesives, sealants [23,25], zinc coating [13].

At the installation and assembly stage, land acquisition, site and access road preparation, and fuel consumption of construction equipment were considered [13,23,25,26]. Transportation of the structures from the production site to the erection site was carried out by sea and road [20–26]. The operation phase of the wind turbines included the repair of the turbine in case of failure, maintenance, including the replacement of oils in the gearbox, generator, cooling system, replacement of the brake system, lubrication of mechanical parts, etc. [20,22,23,25–27]. Waste management at the end of the life cycle includes recycling of up to 81% of recyclable materials (metals - 98%, polymers - 90%, electronics - 50%) [23,25,26], incineration and disposal of non-recyclable components (concrete, composites, oils, paints, etc.).

The LCA of electric vehicles mainly considers three main components: the vehicle frame, the electric axle drive and the battery system. Other resources used in the production of an electric vehicle include textiles [30] and paints and coatings for the body of an electric vehicle [29]. Shipping and freight transport were used to transport materials and parts to the manufacturing plant [29]. During the operation phase of the electric vehicles, maintenance was considered, including replacement of tyres and brake pads. The main stages in the end-of-life phase of an electric vehicle were dismantling, crushing, sorting, waste treatment and recycling of materials [30].

When assessing the life cycle of electric motors for an electric vehicle [13], rolling (steel, aluminium), copper wire drawing and nickel plating were considered as material processing during production. Electronics were considered as auxiliary structures [13].

The LCA studies of passenger aircraft [14,32,33] considered the production of 5 materials (excluding engine materials). The processing of these materials was only discussed in one of the studies [13] and included injection moulding of composites. In the case of aircraft production, the resources considered included water and heat supply [13]. Air and road transport was used to transport materials, parts and structures to the manufacturing plant [29]. Due to a lack of data in the Ecoivent database [13], titanium and nickel were replaced by copper scrap at the end of the aircraft life cycle, as all three metals are classified as first-row transition metals. At the end of an aircraft's life, composites (carbon fibre reinforced plastics) are represented by a stream of mixed plastic waste.

LCA of a bus according to the Ecoinvent database [13] considered 13 types of materials undergoing the following processes: steel rolling, glass tempering and copper wire drawing. A production building for bus assembly was considered as an auxiliary structure. Other resources included heat supply, diesel, lubricating oil, acids, paint (alkyd), etc. The production and disposal stage of the power plants used to operate the bus included the components and materials used for the production of the batteries and for the maintenance, repair and replacement of failed components throughout the life cycle [31].

When assessing the life cycle of gas turbine installation and power plants, 4-8 materials were taken into account [13,14], and materials processing included sheet steel rolling, steel metalworking, welding, injection molding for polymers, and construction work [13]. The foundation and industrial building were used as auxiliary structures [13,14]. Other resources used in the production of the gas turbine plant included heat supply, water and organic chemicals [13,14]. Materials, parts and structures were transported to the production site by car [13] and by truck [14]. In the research [14], the main material flows during the operational phase of a gas turbine power plant (GTPP) are associated with the operation of the plant itself (fuel combustion) and its maintenance (oil, spare parts, etc.). Decommissioning of the GTPP includes dismantling and waste management (incineration and disposal) [14].

It was found that most of the existing studies and databases used between 2 and 15 materials to assess the life cycle of technically complex equipment, while only a few studies took into account the material treatment processes (metalworking, injection moulding, welding, etc.). The main auxiliary structure for the production of technically complex equipment was the foundation, while the other main resources were heat supply, water and lubricating oil. Electricity consumption in the production process was considered in almost all studies. The transport of materials, parts and structures for the production and installation of technically complex equipment was mainly done by freight transport. Most studies considered land acquisition for the installation and assembly of the equipment, while a

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few studies considered site preparation. During the operating phase of technically complex equipment, the main consideration was the replacement of oils and consumables (spare parts, lubricants, tyres, brake pads, etc.). Waste management at the end of the life of technically complex equipment was mainly considered in terms of recycling and disposal.

By analysing the research on the LCA of gas turbine installations and combined cycle gas turbine plants, it was possible to identify the stages and resources that are or are not included in the LCA. In most cases, the LCA of a gas turbine plant considers the stages from extraction of raw materials to disposal of the plant. The LCA of a gas turbine takes into account the production of structural materials (mainly metals), including the dependency on their brand/class (low alloy steel, stainless steel, etc.), energy consumption and waste management at the end of the operation. The LCA of a gas turbine rarely takes into account the technologies for processing structural materials (metalworking, casting, rolling, etc.), the construction of the foundation during assembly and installation, the transport of materials (structures) and maintenance. Repairs, scientific and technical research and development in the production of materials, parts, components, etc. are excluded from the LCA of gas turbines.

Figure 2 shows the life cycle of a gas turbine plant and outlines the LCA boundary used in this study. The components considered in the assessment of the life cycle of a gas turbine plant are a gas turbine engine, a gas turbine engine with power turbine and subframe - a gas turbine unit (GTU) - and a gas turbine unit with foundation (GTI) (Figure 3).

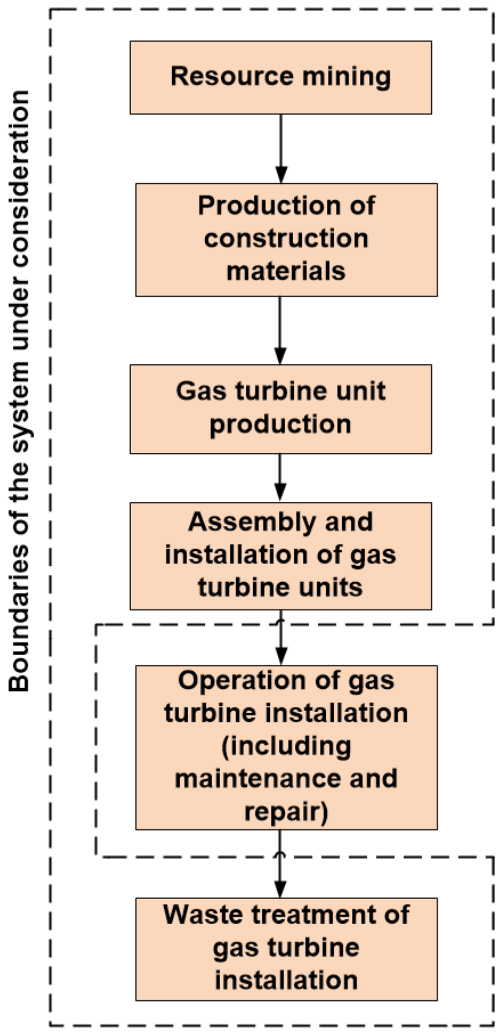

Figure 2. Gas turbine life cycle diagram.

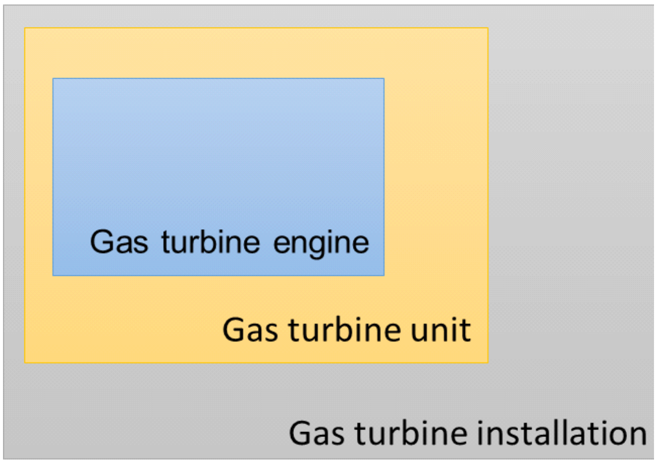

Figure 3. Elements of the gas turbine LCA.

In assessing the life cycle of a gas turbine plant, we consider the following processes and resources: extraction of resources, production of structural materials (steel, aluminium, nickel, titanium), technologies for processing the materials, energy consumption, production of the plant, assembly and installation of the gas turbine plant, recycling of the gas turbine components. The transportation and operation (including maintenance and repair) phases of the gas turbine installation are not included in the LCA of the unit.

In addition, technically complex equipment is characterised by a long period (up to several decades) of research and development (R&D), which is also associated with high resource consumption and environmental impacts. R&D can lead to improved productivity, which helps to increase profits and create an advantage in identifying competitors. For example, it took 25 years to develop and invent a combined cycle gas turbine (CCGT) and 10 years to develop lithium-ion batteries [35]. In practice, however, this phase of research and development is almost never assessed as part of an LCA. This phase is very important because its implementation requires the use of large amounts of resources (electricity, water and heat), labour, time, etc., with corresponding greenhouse gas emissions. The research and development phase is not considered in this study due to the lack or poor quality of open data on production processes in the gas turbine life cycle stages.

2.4. Level of Detail of Material Data

Technically complex devices consist of a large number of materials (more than 30), including various alloys, combined and composite materials. For example, about 35 different types of materials were used to produce the Vestas V110-2.0 MW wind generator [36], and more than 40 materials - to produce the Mitsubishi i-MiEV electric vehicle [29].

A large number of materials are also used in the production of gas turbine equipment. The production of a GTE (PS-90A) gas turbine engine [37], which is used as part of a land-based gas turbine plant, involves more than 50 different materials and alloys, selected with respect to the temperatures and conditions of their use in one or another component of a gas turbine plant. However, it is almost impossible to assess the life cycle of a gas turbine installation by breaking it down into the amount of material used, because of the large amount of labour and time involved. Therefore, as shown above, in practice up to 15 types of materials are used to assess the life cycle of technically complex equipment.

When assessing the life cycle for the construction or production of even the same type of technically complex equipment (e.g. wind turbines), different studies consider different amounts of materials (Table S2).

When assessing the manufacturing phase of wind turbines (offshore and onshore), about 5-15 materials are identified, mainly including metals (iron, steel, cast iron, aluminium and copper alloys, zinc, rare earth metals, etc.), non-metallic materials such as polymers (HDPE, PP), composites (glass and carbon fibre), concrete and epoxy resin [13,20–28].

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Different materials are used to make different parts of wind turbine components. Steel is used in the manufacture of several components, including the tower, nacelle, rotor and foundation [20–24,27,28]. Concrete and steel are important materials for the foundations of wind turbines and are used in different types of turbines depending on the location of the wind turbine, the specific requirements of the turbine manufacturer or the foundation conditions at different sites. Aluminium is used to produce strong yet lightweight turbine components. Copper is mainly used in generator stator and rotor coil windings, high-voltage power cable conductors, transformer coils and earthing [28]. Zinc is used as a protective coating against corrosion of wind turbines exposed to climatic and mechanical influences [13]. Rare earth elements (dysprosium, neodymium) and boron are required for turbine structures using permanent magnets [38]. Epoxy resin composites combined with glass or carbon fibres account for approximately 8-12% of the weight of the turbine and 2-6% of the weight of the equipment. Polymers are mainly used in a turbine (20%) [39].

The breakdown of an electric vehicle requires the use of 14 materials, including metals, polymers, textiles, rubber, etc. By weight, the main material used in the airframe of an electric vehicle is steel, while the main materials used in the body and lithium-ion battery are nickel, cobalt and manganese [30]. Lithium-ion batteries in electric vehicles use a cathode, an anode and an electrolyte as a conductor. The cathode consists mainly of nickel (73%), cobalt (14%), lithium (11%) and aluminium (2%). The anode is usually made entirely of graphite. The electrolyte consists of lithium salts (lithium hexafluorophosphate, LiPF6) in an organic solvent [40].

When assessing aircraft production, about 5 materials are used [13,32,33], such as steel, aluminium, titanium, nickel and composites. A list of materials used in long-haul aircraft (> 4000 km) is given in the study [41], depending on the year of manufacture. The approximate material content for passenger aircraft is 60% aluminium, 25% composites, 12% steel and the remainder nickel and titanium.

When assessing the production stage of electric motors, electric power plants and aircraft engines, about 5-10 materials are used, mainly including metals (iron, steel, cast iron, aluminium and copper alloys, nickel, titanium, etc.), composites (fibreglass), polymers, graphite and lithium pentatitanate (LTO).

In modern aircraft engines, such as those manufactured by General Electric, the main materials are nickel alloys (46%), titanium alloys (25%), steel (16%), aluminium alloys (8%) and composites (4%). Titanium and composite materials make it possible to reduce the weight of engines, which leads to increased fuel efficiency [34].

There is currently little data on consumables used in the manufacture of gas turbines, combined cycle power plants and power stations. When assessing the production stage of gas turbine units, power plants and combined cycle power plants, about 2-15 materials are used, mainly including metals (iron, steel, aluminium and copper alloys, nickel, zinc, cobalt, chromium, etc.), non-metallic materials such as polymers (HDPE) and concrete.

According to the Ecoivent database, 5-8 materials (steel, copper and aluminium alloys, concrete, polypropylene, etc.) are taken into account to evaluate the production of gas turbine units [13]. For example, to assess the life cycle of a combined cycle power plant, only steel and cement are considered [17], as they are the main consumables during the construction phase and the main factors in the budget. In order to carry out the LCA of a mini thermal power plant with gas piston engines, the following materials that make up the power plants were considered in the research work [19]: an engine (steel, cast iron, aluminium), a generator (steel, copper) and a tank (steel).

The analysis of the studies carried out to assess the production/construction phase of technically complex equipment showed that about 2-15 different materials are taken into account, mainly represented by metals and their alloys; non-metallic materials include polymers, composites and concrete (in the case of wind turbines). Therefore, technically complex equipment is broken down into the materials that generate the main greenhouse gas emissions in the production process. On average, 4-5 materials are identified when assessing the production phase of a gas turbine unit, the main ones being metals: steel, aluminium, titanium and nickel.

2.5. Environmental Impact Assessment Categories

The LCA of technically complex products in different studies is carried out according to different impact categories (Table S3).

Based on the reviewed studies that assessed the environmental impacts of technically complex products, the number of categories assessed ranged from 2 to 18. The main categories assessed were: global warming potential, greenhouse gas emissions, total energy demand, ozone depletion, ecotoxicity, depletion of fossil resources and eutrophication. The software products SimaPro [14,22–25,30,32,33] and OpenLCA [15,16] were mainly used to calculate the environmental impacts of technically complex products, while our own calculations based on well-known methods (ReCiPe 2008 [22], Eco-Indicator 99 [33]) were used very rarely. Data from equipment manufacturers and databases (mainly Ecoinvent) were used as sources of information for the calculations; only a few studies used the results of their own research [15,16,32].

Calculations of the environmental impact of wind turbines [20,22–26] were carried out using SimaPro software (different versions), with the Ecoinvent database, data from turbine manufacturers and publications by other researchers as sources of information. The main categories assessed were global warming potential, total energy demand and ozone depletion.

To assess the environmental impact of electric vehicles [29,30], the global warming potential category was mainly used, with manufacturers' data and databases as sources of information (Ecoinvent 3.6, BRUSA, 2019, European Energy Agency, 2016).

The environmental impact assessment of power plants [31] considered two impact categories: CO2 emissions and energy costs. The developed methodology was used for the calculations and the Ecoinvent v.3, GREET, ELPICA databases were used as information sources.

The environmental impact of an aircraft [32,33] was assessed in terms of global warming potential, greenhouse gas emissions, fuel consumption, minerals, etc. The software SimaPro 7.1.8, SimaPro 8 and the Eco-Indicator 99 method were used for the assessment [33], while manufacturers' data, publications, Ecoinvent v.2 and Ecoinvent 3.1 databases were used as sources of information.

A large number of categories from 2 to 11 were used to assess the impact of gas turbine and combined cycle units [14–19], with greenhouse gas emissions being the most commonly used category. The software used included OpenLCA 1.9 - 1.11 and SimaPro 5.1, and the Ecoinvent database, manufacturers' data, our own research and other researchers' publications were used as sources of information.

To assess the environmental impact of gas turbines, greenhouse gas emissions were chosen as the main category because they have the greatest impact at all stages of the life cycle (extraction of raw materials, production of structural materials, production and disposal of gas turbines) and depend on many factors (electricity source, type and consumption of production resources, etc.).

2.6. The GTI under Consideration

The subject of the study is the GTU-16P, which was created on the basis of a gas generator of the PS-90A high-power aircraft engine and the GTU-12P gas turbine unit (developed by Aviadvigatel JSC, Perm, Russia) [42].

The GTU-16P has been produced in series by UEC-Perm Motors JSC (Perm, Russia) since 1999 and is used as a part of the Ural series gas pumping units during the reconstruction of existing gas pumping units, as a drive for the AC electric generators of the GTPP-16PA gas turbine power plants. From 2021, GTU-16Ps produced will be equipped with a single-module low-emission combustion chamber (LECC), which reduces emissions of nitrogen oxides (NOx) and carbon monoxide (CO) [43].

The GTU-16P is used by gas, oil, industrial and other companies: PJSC "Gazprom", OJSC "NK Rosneft", PJSC "T Plus" (Russia), "Botas Petroleum Pipeline Corporation" (Turkey), etc. [44]. As of 1 June 2023, 404 gas turbine units with a capacity of 16 MW are in operation at customers' sites, and their total operating time has reached 13 million hours. The GTU-16P uses mainly natural gas as fuel. The gas turbine plant can use a mixture of natural gas and hydrogen of up to 20% as fuel without changing the design of the combustion chamber [45]. In order to operate a gas turbine power plant using hydrogen fuel in the future, it is necessary to make a number of technological improvements:

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modernising the combustion chamber, changing the size of the fuel line, changing the fuel line system by replacing flanged connections with welded ones, installing safety sensors and leak detectors, modernising the gas turbine control system, etc. [46,47].

The GTU-16P gas turbine unit is located in the power block of the turboblock container. It is a complex comprising the following components:

- PS-90GP-2 gas turbine engine on a sub-engine frame, consisting of a gas generator (compressor, combustion chamber, high-pressure turbine) and a free turbine (Figure 4) [42];
- transmission with casings;
- input device;
- noise-heat-insulating casing;
- output device (snail);
- fuel unit cabinet;
- pipeline and electrical communications.

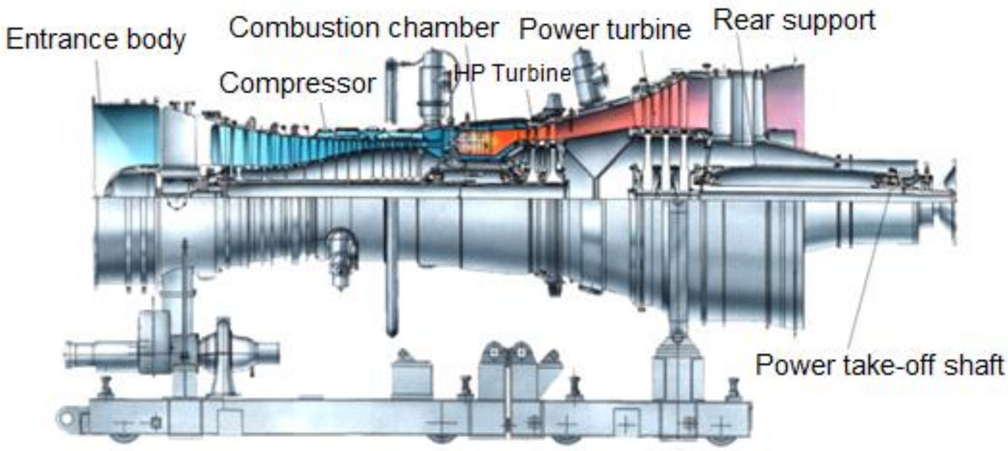

Figure 4. PS-90GP-2 gas turbine engine on a sub-engine frame [42].

The main technical characteristics of GTU-16P are presented in Table 1 [48].

Table 1. Main technical characteristics of the GTU-16P gas turbine installation.

Options	Designation	Value
Power turbine shaft power (performance)	MW	16,0
Efficiency on the power turbine shaft	%	35,2
Total efficiency	%	84,7
Gas temperature in front of the gas generator turbine	°C	1196
Exhaust gas consumption	kg/s	54,7
Gas temperature behind the gas generator turbine	°C	805
Temperature of gases behind the power turbine	°C	540
Fuel consumption	kg/h	3350
Overall dimensions (LxWxH)	mm	8250x3200x3200
Weight (dry)	kg	5150
Full installation resource	thous. h	100
Gas generator life before major overhaul	thous. h	25
Power turbine service life before major overhaul	thous. h	50

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3. Results

3.1. Assessment of the Carbon Footprint of Gas Turbine Installation

In accordance with the methodology described above, an assessment of the carbon footprint of the GTI during its production and use in Russia has been made. The boundaries of the system are defined by the production of structural materials, including material processing, production of the gas turbine unit, production and installation of the foundations for the gas turbine unit, waste management at the end of the life of the gas turbine unit). The stages of GTI operation and transportation of materials, raw materials and other resources were not considered as these stages were not included in the objectives of this study.

The life cycle inventory of the GTA included the collection of data on the main flows of structural materials, both qualitatively and quantitatively. In determining the material consumption for the GTU-16P based on the PS-90GP-2 aircraft engine, the material content of the CF6 aircraft engine (General Electric, USA) was used as an analogue [49]. The sub-engine frame and other elements of the gas turbine unit were assumed to be made of structural steel. The materials used in the manufacture of the GTU-16P and their manufacturing processes are shown in Table 2. The main materials used in the production of the GTU are steel (51%) - structural and stainless (chromium), and nickel alloys, which make up a fairly high percentage (about 30%) and are used in the combustor and turbines (Figure 5).

Table 2. Inventory analysis in the gas turbine unit production.

Name	Volume of work	Accepted data for impact calculation
Production of construction materials		
Structural alloy steel, kg	2150	Market for steel, low-alloyed… RoW
Stainless steel (chromium), kg	480	Market for steel, chromium steel 18/8... hot rolling... GLO
Titanium alloys, kg	750	Market for titanium… GLO
Nickel alloys, kg	1530	Market for nickel, class1… GLO
Aluminum alloys, kg	240	Market for aluminum, cast alloy…GLO
Material processing		
Structural steel casting, kg	2150	Market for casting, steel, lost-wax… GLO*
Metalworking, average for the production of structural steel products	2150	Metal working, average for steel product manufacturing… RoW
Rolled stainless steel, kg	480	Hot rolling, steel… RoW
Metalworking, medium for the production of steel products	480	Metal working, average for chromium steel … RoW**
Metalworking, average for the production of titanium alloy products	750	Metal working, average for chromium steel … RoW**
Metalworking, average for the production of products from nickel alloys	1530	Metal working, average for chromium steel … RoW**

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Aluminum casting, kg	240	Market for casting, aluminum, lost-wax… GLO*

* Includes mould making, alloy melting, casting, dewaxing, cutting, grinding, straightening, machining. ** Metalworking technology for titanium and nickel alloys is adopted as for steel (chromium), due to similar product production technologies and melting temperatures.

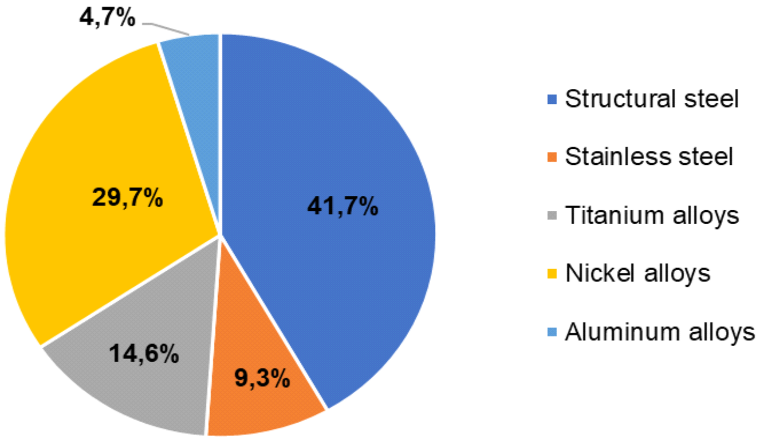

Figure 5. Distribution of materials used in the production of gas turbine units (% by weight).

At the stage of production and installation of the foundation for the gas turbine unit, the costs of materials for the foundation, land acquisition works (including transfer of land to another category) and site preparation were considered, taking into account the energy resources for their implementation (electricity, heat supply, fuel for construction equipment) (Table 3). The data for the inventory analysis during the production and installation of the foundation for a gas turbine unit were taken from the Ecoinvent 3.8 database for a similar installation (10 MW gas turbine unit) [13].

Table 3. Inventory analysis during the production and installation of foundations for gas turbine units.

Name	Volume of work	Accepted data for impact calculation
Concrete, m^3	50,0	Market for concrete, normal… RoW
Copper (cathode), kg	5000	Market for copper, cathode…GLO
Low pressure polyethylene, kg	15000	Polyethylene, high density, granulate
Reinforcing steel, kg	47500	Reinforcing steel
Diesel fuel (for operation of construction equipment), MJ	759000	Market for diesel, burned in building machine…GLO
Electricity, kW	46900	Market for electricity, medium voltage …GLO
Heat supply, MJ	721050	Market for heat, district or industrial, other than natural gas… RoW
Land allocation (industrial zone), m^2/year	15000	Resource / land_Occupation, industrial area
Conversion of land of undetermined purpose, m^2	1000	Resource / land_Transformation, from unspecified
Transfer of land to an industrial zone, m^2	1000	Resource / land_Transformation, to industrial area

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The waste management phase at the end of the life of the gas turbine plant involves dismantling, sorting and recycling of the construction materials (Table 4). Approximately 80% of the materials used in the manufacture of gas turbine units should be recycled according to the manufacturers' recommendations. The calculations are based on data confirming that the materials generated at the end of the gas turbine unit's service life are waste.

Table 4. Inventory list of waste management after the end-of-life operation of a gas turbine installation.

Name	Volume of work	Accepted data for impact calculation
Waste of gas turbine unit		
Steel waste (steel scrap), kg	2630	Market for scrap steel…RoW
Titanium waste (titanium scrap), kg	750	Market for scrap copper…RoW *
Nickel waste (nickel scrap), kg	1530	Market for scrap copper…RoW *
Aluminum waste (aluminum scrap), kg	240	Market for scrap aluminium…RoW
Waste of foundation		
Reinforced concrete waste, kg	167500	Market for reinforced concrete…RoW
Copper waste (copper scrap), kg	5000	Market for scrap copper…RoW
low pressure polyethylene waste, kg	15000	Market for waste polyethylene…RoW

* Due to the lack of values in the database for the carbon footprint of titanium and nickel at the end of life of the gas turbine unit, data for copper scrap are used, since all three metals are considered first-row transition metals.

Figure 6 shows the carbon footprint of the life cycle stages of the gas turbine installation.

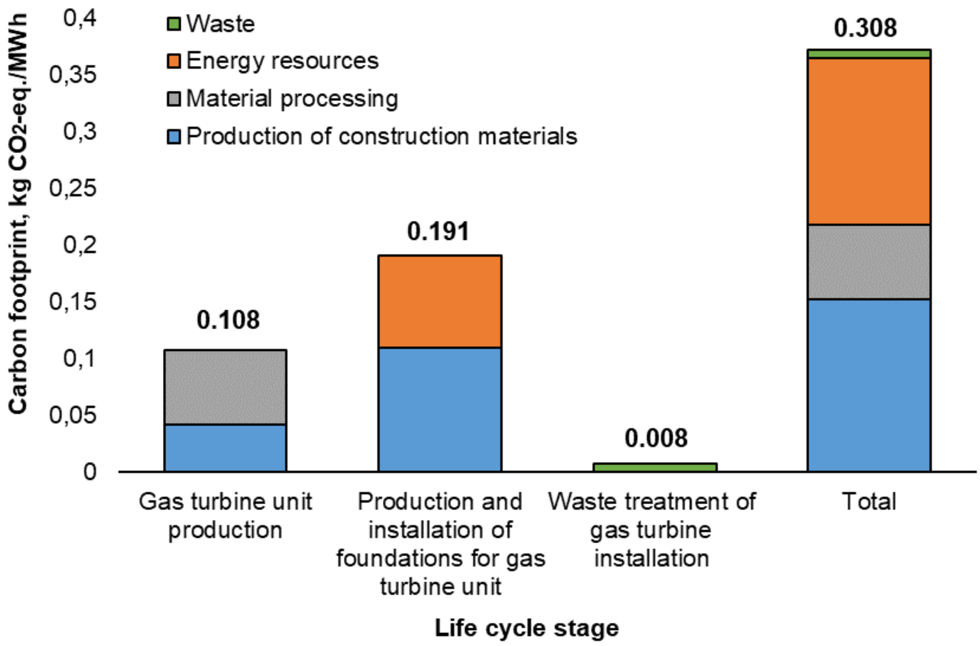

Figure 6. Carbon footprint at the stages of the gas turbine installation life cycle.

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On the basis of the data obtained on the carbon footprint of the stages of the GTI life cycle per MWh of electricity produced, it was determined that the main contribution comes from the manufacturing and installation of the foundation for the gas turbine unit (62% of total emissions), consisting of the carbon footprint of the production of materials (0.11 kg CO_2-eq./MWh) and the consumption of energy resources (0.08 kg CO_2-eq./MWh). The carbon footprint of the production of the GTI was 0.108 kg CO_2-eq/MWh (35.2% of the total emissions), with the majority of the carbon footprint coming from material processing (0.066 kg CO_2-eq/MWh). The recycling of the gas turbine unit and the foundation for the GTI had the smallest carbon footprint - 0.008 kg CO_2-eq/MWh (2.7% of total emissions). The largest carbon footprint among the considered processes, resources and works was the production of materials - 0.153 kg CO_2-eq/MWh, which represents half of the total emissions from the life cycle stages of the gas turbine unit.

For comparison, the carbon footprint of the 10 MW GTI [13] is 0.374 kg CO_2-eq/MWh and includes the production of the gas turbine unit (only steel was considered) and the production of the foundation for the GTI, but excludes the processing of materials during the production and disposal of the gas turbine unit.

The carbon footprint of a gas turbine unit is highly dependent on the carbon footprint of the individual materials. The carbon footprint of the production of basic metals depends on the technology and production method (e.g. blast furnace or electric arc furnace for steel), the raw materials used (virgin or recycled), the electricity source used (thermal, nuclear, renewable, etc.), the alloy brand, etc. Table 5 shows the carbon footprint of the main metals used in the production of technically complex equipment. The carbon footprint values of the metals used for the calculations (from the Ecoinvent 3.8 database) are between the minimum and maximum values shown in the Table 5.

Table 5. Carbon footprint of basic metals production.

Metal (alloy)	**Carbon footprint, t CO_2-eq. / t metal**					
	Accepted values	**Average value**		**Depending on production method/brand**	**Depending on the energy source**	**Using recycled materials**
		In the world	**In Russia**			
Steel	1,89 (structural steel) 5,07 (stainless steel)	1,4 -1,85 [50,51]	1,4 [51]	2,32 (BF-BOF) 0,67 (EAF) 1,65 (DRI-EAF) [52] / 6,15 (stainless steel) [53] 1,8-5,5 (stainless steel) [54]	1,9 (coal) [55] 1,4 (Renewable energy sources and natural gas) [55,56] 0,76 (Renewable energy sources and hydrogen) [55,56]	0,4 [55]
Aluminum	5,51	12,5 [57,58]	4,0 [59]	4,28 (alumina electrolysis) [60] 0,01 (inert anode technology) [57]	16,5 (coal) 7,5 (natural gas) 2,4 (hydroelectric power station) [57]	0,6 [58]
Titanium	46,06	18,5 [53,61]	no data	16,9 (Titanium 6-4 alloy) [62] 35,6 (Kroll method) [63]	no data	3,2 (Titanium 6-4 alloy) [62] 7,8 [65]

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				55,0 (6Al-4V alloy) [64]		
Nickel	16,67	13,0 [66,67]	8,1 [68]	7,2 (class 1 sulphide ore) [69] 27,5 (class 1 from laterite ore) [70] 45,0 (class 2 laterite ore) [71] 8,5 (Inconel 718 alloy) [62]	16,0 (coal) 14,0 (grid mix) 7,0 (hydroelectric power station) 6,0 (natural gas) [72]	1,6 (Inconel 718 alloy) [62]

BF-BOF – Blast furnace and basic oxygen furnaces. EAF – electric arc furnace. DRI-EAF – production in an electric arc furnace based on direct reduced iron (DRI).

The global contribution of the metallurgical sector to total greenhouse gas emissions is about 9% [73].

To produce the GTI of the unearthly type, steel is one of the main metals used. According to the International Energy Agency (IEA), the carbon footprint of steel is 1.4 tonnes of CO2-eq. /t of steel produced and 1.85 tonnes CO_2-eq. / t according to the World Steel Association (WSA) [50,51]. The intensity of CO_2 emissions from steel production is influenced by the country's industrial structure, technology, fuel choice, emission factor, steel plant capacity utilisation and materials (e.g. availability of steel scrap) [73]. Each tonne of scrap used to make steel avoids 1.5 tonnes of CO_2 emissions and the consumption of 1.4 tonnes of iron ore, 740 kg of coal and 120 kg of limestone [74]. The CO_2 emissions in steel production from the recycled materials are 0.4 CO_2-eq./t of steel [52].

Steel is produced through two main technological chains: blast furnace (BF) steelmaking, which is based on the process of reducing iron ore in a blast furnace (BF) followed by the combustion of carbon from the pig iron in a basic oxygen furnace (BOF), and electric arc furnace (EAF) steelmaking, which is remelted either with scrap or with direct reduced iron (DRI). According to the WSA, BF-BOF uses 13.8% of scrap with emissions of 2.32 t CO_2-eq./t of steel, while EAF uses 105% of steel scrap with emissions of 0.67 t CO_2-eq./t. [52]. China is the largest steel producer and the amount of CO_2 per tonne of steel in China is higher than in other countries. This is because almost all steel in China is produced in blast furnaces. Steel production in Europe is less polluting because 40% of steel in Europe is produced in electric arc furnaces [75].

CO2 emissions are influenced by the source of electricity, as in the case of steel produced using electricity. According to the International Energy Agency's (IEA) "Net Zero Emissions by 2050 Scenario" roadmap, the share of energy from renewable sources will increase from the current level of 10% to 60%, provided by solar, wind and hydro power engineering. The share of fossil fuels is reduced from 80% to about 20% [76]. Coal currently provides about 75% of the steel sector's energy and raw material needs, which is comparable to its share in the last decade. According to Net Zero Emissions (NZE), the share of emission-intensive blast furnaces in steel production will be reduced by about 10% by 2030 as existing plants are phased out [50].

The aluminium industry is responsible for more than 1% of global anthropogenic greenhouse gas emissions [7]. Over the past decade, the average global direct emission intensity of aluminium production has declined moderately, by an average of 2% per year. However, according to the NZE scenario, this decline will accelerate significantly to 4% per year by 2030 (18%) as a result of reductions in alumina refining and primary and secondary aluminium production [77]. According to the International Aluminium Institute (IAI), the global average carbon footprint of primary aluminium production is 12.5 t CO_2-eq./t, and 0.6 t CO_2-eq./t when using recycled materials. [58]. The energy cost of aluminium remelting is only 5% of the energy cost of primary aluminium production [78].

Currently, almost all primary aluminium smelting processes use carbon anodes, which release CO_2 during the electrolysis process. The use of inert anodes and increased scrap production could help replace existing emission-intensive industries. By 2030, inert anodes will be used in about 7% of primary production [77]. The "TÜV AUSTRIA Standards & Compliance" division conducted an independent verification of greenhouse gas emissions in the aluminium production process at the

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Krasnoyarsk aluminium plant "RUSAL" (Russia) and confirmed that aluminium produced using inert anode technology and hydroelectric power has specific emissions at the level of 0.01 t CO_2-eq./t of metal [79].

68% of the world's primary aluminium is produced using non-renewable energy sources (coal, natural gas) [80]. Since 2010, the share of coal has increased and the share of hydropower has decreased, mainly due to the growing share of aluminium production in China, where more than 80% of production is coal-fired. In Europe, North America and South America, more than 80% of production is hydroelectric. By 2030, the emissions intensity of the entire power generation structure will be reduced by around 60% compared to today's levels due to renewable energy sources. China has announced that, as part of its "Pollution Reduction and Carbon Emission Reduction Synergy Plan", the production of recycled aluminium will reach 11.5 million tonnes by 2025 and the share of renewable energy sources will increase by more than 30% by 2030 [77].

The carbon footprint of titanium production depends on many factors, such as primary raw materials, production technology, source of electricity, and ranges from 1.0 to 36.0 t CO_2-eq. [53,61]. Up to 2.8 t CO_2-eq. per tonne of natural rutile used can be saved compared to upgrading/beneficiation of ilmenite by smelting and chemical processes to produce high quality titanium raw materials, such as titanium dioxide slag and synthetic rutile [65].

The LCA conducted by "EarthShift Global" found that the "IperionX" recycled titanium powders to be produced at the company's planned demonstration plant in Virginia (USA) using its proprietary technology, could have the life cycle carbon footprint of only 7.8 t CO_2-eq. / t [65]. That is more than 90% lower than with traditional titanium powders produced by plasma atomization, and 80% lower than with a titanium ingot obtained by the Kroll method (35.58 t CO_2-eq./t) [63]. However, to use the recycled titanium alloys completely for the manufacture of new parts for the GTI is not possible, due to a decrease in strength properties and resistance to corresponding temperatures.

According to the Nickel Institute data, the global average carbon footprint of Class 1 nickel is 13.0 t CO_2-eq. / t of the finished products [66,67]. China accounts for about 31% of global nickel production [66], using mainly coal as an energy source. According to research [72], nickel produced using mixed energy sources (grid mix) is 14.0 t CO_2-eq. / t, hydropower – 7.0 t CO_2-eq. / t., natural gas energy – 6.0 t CO_2-eq. / t. The main producer of nickel in Russia is the Norilsk Nickel company, which has one of the highest shares of renewable energy use (HPS) - 47% (2021) [68].

Nickel and its alloys, including corrosion-resistant and high-temperature alloys (used in the combustion chamber, high-pressure turbine and power turbine of the GTI), are almost 100% recyclable and can be recycled indefinitely without loss of their quality. Nickel retains most of its primary metal value, with high-grade scrap typically containing at least 95% of the primary metal value. Recycling nickel requires approximately 20% of the energy required to extract and process the primary metal [78]. For example, the estimated carbon footprint of 1 tonne of the primary nickel alloy "Inconel 718" is 8.507 t CO_2-eq. / t. The greenhouse gas emission reduction of recycled Inconel 718 nickel alloy is 6,940 t CO_2-eq. / t [62].

Thus, the carbon footprint of individual materials used in the production of a GTI can affect the final carbon footprint of the gas turbine installation. The carbon footprint of metal production is also influenced by the country-specific fuel conversion factors used, CO2 emission factors from the country's electricity grid, and factors for auxiliary/intermediate materials. Depending on the source of electricity production, the carbon footprint of producing 1 kWh of electricity may differ: coal - 820 g CO_2-eq., natural gas - 490 g CO_2-eq., biomass - 230 g CO_2-eq., solar energy - 41-48 g CO_2-eq., hydropower – 24.0 g CO_2-eq., nuclear energy – 12.0 g CO_2-eq., wind energy (sea) – 12.0 g CO_2-eq., wind energy (unearthly) – 11.0 g CO_2-eq. [81].

When assessing the life cycle of technically complex equipment, the amount and type of primary energy consumed in the production of electrical energy is of great importance. The structure of generation capacities in different countries, as well as in different regions within the same country, differs significantly and depends on climatic and geographical conditions, availability of hydrocarbon fuels, natural resources, level of technological development, etc. [31].

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Currently, there is a problem in assessing the carbon footprint of electricity generation in Russia due to the lack of uniform, generally accepted regional coefficients for electricity generation. When calculating emission factors for the energy system, emissions for all types of energy production (thermal, nuclear, hydroelectric, renewable, etc.) are averaged and “evenly distributed” among all consumers - no account is taken of the specifics of electricity production and no adjustment is made for the import/export of electricity within the boundaries of the respective territory (region).

The carbon footprint of the electricity used to produce materials clearly has a large impact, which in turn affects the carbon footprint of the GTI itself. The use of renewable electricity to produce metals (e.g. green steel) will have a much lower carbon footprint than the use of fossil fuel energy.

4. Discussion

In order to compare the results obtained in assessing the carbon footprint of a gas turbine plant, research results for other technically complex electricity generating plants - a wind turbine, a fuel cell and a gas turbine plant - were used (Table 6).

Table 6. Carbon footprint of technically complex devices.

Object	Carbon footprint (kg CO_2-eq/MWh)
Wind turbine	3,0-45,0 [23,25,82–87].
Fuel cell	30 -391 [88,89]
Gas turbine installation	0,374 [13] 0,98-4,72 [17] 47,0-54,3*[17] 457-575 (natural gas)** 602-757 (light fuel oil)** 629 (heavy fuel oil)** [90]
Gas turbine installation (own research)	0,308

* taking into account hydrogen fuel production and electricity production. ** taking into account the operational stage (fuel combustion).

Analysis of greenhouse gas emissions over the life cycle of wind energy systems allowed us to determine the range of carbon footprint values - from 3.0 to 45 kg CO_2-eq./MWh (the average value is 11.0 kg CO_2-eq. /MWh) [23,25,82–87]. The main carbon footprint comes from the stage of producing materials and components of the wind turbine (87.2%) [20].

The carbon footprint of solid oxide fuel cells (SOFCs) depends on their power. Building a “typical” 1 kW SOFC battery results in emissions of 410–530 kg CO_2-eq./MWh, and will require 7.1–9.9 GJ of primary energy, 60% of which is spent on sintering cells. The research [88] determined that the carbon intensity of electricity production from an average SOFC is about 355 kg CO_2-eq./MWh, and taking into account the construction of chimneys and an exhaust gas purification system, it increases to 391 kg CO_2-eq./MWh. For 1 MW SOFC, the average hourly greenhouse gas emissions of SOFCs are about 30 kg CO_2-eq. /MWh [89].

The carbon footprint of gas turbine installation, taking into account the stages of production and storage of hydrogen fuel and electricity production (wind energy), during the GTI production is 47.0-54.3 g CO_2-eq./kWh. At the same time, the carbon footprint in the production of gas turbine installation, taking into account the production of steel and concrete, amounted to 0.98-4.72 g CO_2-eq./kWh [17]. The carbon footprint of gas turbine installations, taking into account emissions from fuel combustion, increases significantly: when using natural gas - 457-575 t CO_2-eq./GW, diesel fuel - 602-757 t CO_2-eq./GW, and fuel oil - 629 t CO_2-eq./GW [90].

Thus, the carbon footprint at the stages of the gas turbine life cycle, based on the results of our own research, is relatively comparable to the carbon footprint of other technically complex devices. The obtained value of the carbon footprint of the gas turbine installation is lower with greater

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consideration of input parameters, which indicates the effective use of the GTI for electricity production in terms of greenhouse gas emissions.

5. Conclusions

Hydrogen is a promising energy resource for industrial decarbonisation and can be used in energy carriers such as fuel cells, combustion engines and gas turbines, hydrogen power plants for transport and energy. Gas turbines are widely used to generate electrical and thermal energy. Currently, the use of GTIs to burn hydrogen as part of the development of hydrogen energy is of particular interest. In order to assess the prospects of this trend towards the use of GTIs, it is necessary, among other things, to understand the carbon footprint of the GTI as part of the carbon footprint of the whole life cycle of hydrogen.

The assessment of the greenhouse gas emissions at the different stages of the GTI life cycle per MWh of electricity produced showed that the largest carbon footprint is that of the production and installation of the foundation for the gas turbine unit (62% of the total emissions), consisting of the carbon footprint of the production of materials and the consumption of energy resources. The carbon footprint of the production of the gas turbine unit was 35.2% of the total emissions, with the processing of materials accounting for the majority of the carbon footprint. The largest carbon footprint among the considered processes, resources and works was the production of materials - 0.153 kg CO_2-eq./MWh, which is half of the total emissions of the gas turbine life cycle stages. Based on the results of our own research, the total carbon footprint of the gas turbine installation life cycle stages (0.307 kg CO_2-eq./MWh) is relatively comparable to the carbon footprint of other power generation equipment.

Thus, the reliability of the results of assessing the carbon footprint of the GTIs in Russia is in most cases associated with the quality of the initial data, the absence or low quality of open data on production processes at the stages of the life cycle of the GTIs. To solve these problems, it is necessary to create a clear methodology for assessing the carbon footprint at all stages of the GTI life cycle, taking into account the specifics of the technologies used (processes of obtaining and converting materials, use of resources, auxiliary production processes, etc.), development of a methodology and information base with substantiated data on materials, energy sources and technologies that can be used to calculate greenhouse gas emissions.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org, Table S1: Stages and resources taken into account when assessing the life cycle of technically complex devices; Table S2: Materials used for the production/construction of technically complex devices; Table S3: Impact categories used when assessing technically complex devices.

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