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A life cycle assessment study of European Space Agency's space tracking terminal†

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The transition to a low-carbon and resource-efficient circular economy is a political pillar of the EU and a priority for space agencies. Indeed, the space industry is pursuing sustainable development practices to reduce the environmental impacts. Life Cycle Assessment (LCA) is internationally recognized as the most appropriate methodology to estimate the environmental impacts of products, processes, and services and to evaluate the effectiveness of sustainability strategies related to reducing these negative externalities. To support the European Space Agency (ESA) in the process of planning more sustainable eco-design solutions, the objective of this paper is the development of a cradle-to-grave screening LCA study to assess the environmental impacts concerning the ESA's ground-based satellite tracking system based in New Norcia (AU) along its entire life cycle, including the tracking antenna and the photovoltaic panels. This scenario has been compared with 2 other scenarios to verify whether the use of photovoltaic panels has a benefit in terms of environmental impact (scenario A) and to understand the consequences in changing the location of the station, from New Norcia to Cebreros (E) by considering the change in the national energy mix from the Australian to the Spanish (scenario B). This study is one of the first attempts to apply the LCA methodology to the space sector, and its results, conducted according to ISO 14040/44 2021 guidelines and by means of the ReCiPe calculation method (2016), will be exploited by the ESA to plan a more sustainable eco-design for the construction of future space tracking stations.

Environmental significance

The transition to a low-carbon and resource-efficient circular economy is now a priority for many European countries and a political pillar of the European Union. Over the last decade, the space sector has shown a lack of commitment to reducing environmental impacts, and only recently space agencies have begun to implement a wide range of programs for the achievement of the Sustainable Development Goals (SDGs) and adaptation to sustainability standards. This study is one of the first attempts to apply the LCA methodology to the space sector, and its results will be exploited by the ESA to plan more sustainable eco-designs for the construction of future space tracking stations. Specifically, the objective of this paper is to support the European Space Agency in the assessment of the environmental impacts caused by ESA's space-tracking station based in New Norcia (AU) by developing a cradle-to-grave screening Life Cycle Assessment (LCA) study. The above-mentioned topic is in line with the aim of the journal Sustainable Production and Consumption, which states that all papers should include some elements of life cycle thinking and should clearly demonstrate that they are addressing topics related to sustainable production and consumption, specifically on the points: life cycle management and life cycle thinking.

1 Introduction

The transition to a low-carbon and resource-efficient circular economy is now a priority for many European countries and a political pillar of the European Union as well.[1] From a perspective of sustainable development, eco-design is crucial to promote green technologies, to understand how much space activities pollute, to recognize alternatives to reduce the environmental impacts and to identify different processes or technologies that can be used to reduce these negative externalities.[2] To assess the environmental impacts of each space project, it is important to assess emissions and consumed resources over a mission's life cycle.[3,4] To this end, ESA is experimenting eco-

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design activities (*i.e.*, new technologies), intending to mitigate the environmental impacts of space missions and ground infrastructure by designing missions in a more environmentally friendly way, without compromising the performances of space missions.[4,5] Therefore, intending to support the identification of technologies that have this lower environmental impact and maximise the benefits for the environment, various players in the space industry, including the ESA, have begun to adopt the methodology concerning the life cycle assessment (LCA).[2,6–8] The objective of this paper is to support the European Space Agency in the assessment of the environmental impacts caused by ESA's space-tracking station based in New Norcia (AU) by developing a cradle-to-grave screening Life Cycle Assessment (LCA) study. This study is one of the first attempts to apply the LCA methodology to the space sector, and its results will be exploited by the ESA to plan more sustainable eco-design for the construction of future space tracking stations.

1.1 Literature review

Over the last decade, the space sector has shown a lack of commitment to reducing environmental impacts. Nowadays, however, it is no longer possible to accept that emissions and other environmental impacts associated which space activities are not properly accounted for and reduced. Accordingly, space agencies have begun to implement a wide range of programs for the achievement of Sustainable Development Goals (SDGs) and adaptation to sustainability standards.[8–15] Specifically, in 2019, the member states of the United Nations Committee for the Peaceful Uses of Outer Space (UN COPUOS) reached an agreement through the stipulation of a series of guidelines for the long-term sustainability of space applications to reduce their environmental impacts.[8,15] Following the indications provided in these agreements and to cope with the increase in space activities and the growing number of stakeholders in this sector, it has been possible to develop and promote technologies that minimize environmental impacts and maximize the use of renewable resources.[8]

2 Materials and methods

2.1 New Norcia European Space Tracking (ESTRACK) ground station

The ESA's tracking station network (ESTRACK) is a global system of ground station sites, established in 1975 for the International Ultraviolet Explorer mission and located in different places around the world that provides links between the European Space Operations Centre (ESOC) in Darmstadt (Germany) and the ESA satellites with the aim of maximizing the observable area of space.[16–19] The ESTRACK stations and their associated site infrastructure have different functions depending on the antenna available, and for this circumstance each station can participate in a particular type of space mission.[20] To face the expected rapid increase in the number of interplanetary missions, the ESA has started building more deep-space antennas.[18] The deep-space tracking network, being part of the ESTRACK core network, consists of a set of three 35 meter-class ground stations that are suitable for a wide range of missions, such as, *e.g.*, (I) interplanetary missions, (II) space astronomy activities, (III) solar observation and (IV) lunar exploration.[17–20] Each station has one or more antenna terminals which include a satellite dish and related radio signal processing equipment.[18,19] The signals received from space stations gather radiometric data that help mission controllers to collect specific information, such as, *e.g.*, the location, trajectory, and velocity of their spacecraft as well as atmospheric and meteorological data.[18,19] Specifically, the ESA began acquiring a first deep-space antenna in New Norcia composed of two terminals, New Norcia – 1 (NNO-1), built in 2001, and New Norcia – 2 (NNO-2), built later in 2015, both located at 126 kilometres North of Perth in Western Australia.[17,20,21] In this paper, the Australian NNO-1 antenna will be the focus of the assessment, while data from the Spanish stations Cebreros and Malargüe (two stations of similar composition and use to the Australian NNO-1 antenna) will also be used in case primary data for the station located in New Norcia are missing.

The antenna used in the three locations mentioned above is a Cassegrain beam wave guide antenna,[17] a parabolic antenna where the feed antenna is mounted behind the surface of the concave main parabolic reflector dish and is aimed at a smaller convex secondary reflector suspended in front of the primary reflector.[22] The antenna is fitted with a shaped 35 meter parabolic main reflector and a shaped hyperbolic sub-reflector in an elevation over an azimuth mount.[17,21] Furthermore, the New Norcia station has a power plant designed to supply a reliable electricity source to all power units. The latter provides a short-break (SB) power supply using diesel generators and a no-break (NB) power supply using static converters and batteries. The diesel generators supply each with 520 kW within 1–2 minutes after public power failure. In addition, two modular converters supply each 300 kW, the latter can be extended to 480 kW, and the battery capacity allows for a maximum bridging time of 6 minutes, sufficient time for the possible short of a diesel generator.[20] A control centre adjacent to the terminal manages all operational functions. At this centre, there are emergency fire management systems as well, which include rainwater collection tanks that are treated with active coal and UV for human consumption and emergency use. The total storage capacity is approximately 340 m^3 collected from about 700 m^2 of the roof surface. Furthermore, as of 2017, the New Norcia station is being powered in part by sunlight, by employing the installed photovoltaic panels arranged in five double rows.[19]

2.2 Organization of the study

The objective of this study is to perform an LCA study following ISO 14044/2021 for the New Norcia – 1 (NNO-1) station composed of the "terminal", the "power plant", and the "photovoltaic panels". The notion "terminal" denotes the antenna and all associated signal processing equipment (see Fig. 1). While the "power plant" is composed of main and backup power systems, *i.e.* the diesel generators, the batteries, and the modular UPS transformers. Low voltage panels (*i.e.*, mostly copper bars and metallic cabinets with circuit breakers)

Fig. 1 New Norcia 35 m terminal.

were initially to be included in the study, but due to the lack of specific data, it was decided to remove them from the assessment. For the same reason, the "OPS building" operations centre was also omitted from the study due to insufficient data. Furthermore, in addition, for a benchmark analysis, other different scenarios were compared both to verify whether the use of photovoltaic panels had a benefit in terms of environmental impact (scenario A) and to understand the distribution of the impacts in the change of the location of the station, from New Norcia to Cebreros, specifically in the change of the national energy mix from the Australian to the Spanish one (scenario B). The study was carried out using SimaPro software (version 9.3). Among the databases contained in the program, it was decided to utilise Ecoinvent (version 3.8). When data from a specific supplier are unknown, the Ecoinvent market process has been used. For this circumstance, these market processes include inputs from production in several countries or a single country; in addition, inputs from transport processes are included. Indeed, transformation processes contain all the inputs for making a product or service, excluding transport processes, and inputs from all the associated emissions and resource extractions.

2.3 Functional unit and system boundaries

In an LCA study, all flows into and out of the system are allocated according to the functional unit. The functional unit chosen in this paper is one year of activity of the station, as can be seen in Table 1. The station has a life cycle of about 50 years if all maintenance is considered. The period of activity during which the antenna communicates with a satellite is called "pass". On average, during 2020, there were 1142 passes, of which 975 passes were during the operational phases, 17 passes during tests and simulations and 150 passes under maintenance periods. The choice of this functional unit is supported by a review of scientific articles, which revealed that for ground space-tracking infrastructure the most used functional unit is precisely one year of operation of the station.[8,9,23,24] Depending on the objective of the study, the system boundaries delimit the physical environments, operations, and production processes to be considered. This LCA was carried out using a "cradle-to-grave" approach, which means that all the processes used for the functioning of the structure will be quantified, starting from the acquisition of raw materials up to its end of life.

2.4 Inventory data

As introduced above, the New Norcia station is made up of various components. Specifically, Fig. 2 presents the flowchart of the case study under assessment, which provides information on the materials and processes involved. For modelling the scenario represented and summarized in the flowchart, the ESA provided primary data for:

- Emissions.
- Energy and fuel consumed during the construction of the station.
- Fuel consumption.
- Life cycle of the antenna.
- Maintenance procedures.
- Mass, quantity and type of components for the power plant.
- Mass, quantity and type of components for the photovoltaic plant.
- Mass, quantity and type of materials for the construction of the antenna.
- Mode of transport, mileage and characteristics of the vehicles used.
- Procedures for and characteristics of disposal.
- Voltage, supply and consumption of electricity.
- Water consumption.

Following general LCA cut-off rules, some components have been considered not relevant for the study. The threshold of 1% impact has been applied, which considering the very low amounts of some of the involved processes caused their exclusion from the assessment as reported below:

- Low voltage panels.
- Cooling machines.
- Operative station building (OPS) and its materials.
- Employee's water consumption.

All identified processes have been selected from the Ecoinvent 3.8 database, and the system model used is "cut-off",

Table 1 Study information summary

Function	Transmitting and receiving signals to and from space
Functional unit	One year of station's activity; 1142 passes on average
System boundaries	Raw materials, assembly of the terminal, use phase & downstream
Life cycle	50 years with maintenance

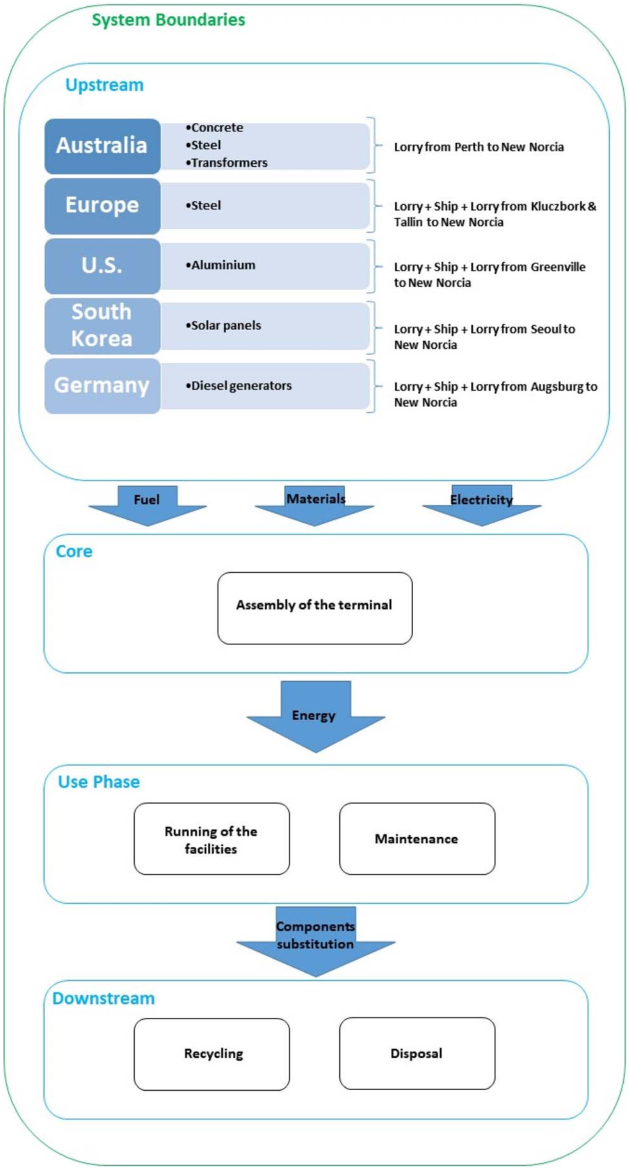

Fig. 2 Flow chart of NNO-1 used to model the LCA study.

whose underlying philosophy is that a producer is fully responsible for the disposal of the waste and that the latter receives no credit for the supply of recyclable materials (Ecoinvent, 2017 [25]). Furthermore, in the choice of the different processes, the geographical reference of the data was also considered since each activity present in Ecoinvent refers to a specific geographical position. This can refer to the whole world (GLO or RoW), a region made up of several countries (*e.g.*, RER), a country (*e.g.*, AU) or a smaller area (*e.g.*, a province). Whenever possible, the processes referring to Australia were considered for this analysis, which is more suitable for representing the Australian context. Where not possible, the "global" and "rest of the world" processes were considered. Moreover, where possible the processes used were of the transformation type, and only some exceptions were of the market type. For more information about the different components used for the study, please refer to the ESI S1.†

In the next subsections, the different components of the station evaluated within this LCA study ((i) "antenna", (ii) "power plant", (iii) "photovoltaic plant", (iv) "electricity consumption and production", (v) "fuel consumption", (vi) "maintenance" and (vii) "disposal") will be described.

2.4.1 Antenna. The 35 m antenna of the New Norcia site can be divided into three sections:

• Upper section (aluminium and steel): the main component of the whole antenna due to its signal reception function.

• Middle section (concrete and steel): it has a support function and acts as a counterweight to balance the entire antenna.

• Lower section (concrete and steel): it has important supporting and structural functions.

The quantities of the materials used for the antenna construction, the distribution of its components in the three sections and the information regarding their transport to the site are summarized in Table 2.

Within this study, the impact related to the operation of the building machines is also considered. Specifically, ESA managers have made it clear that 412280 kW h were consumed in 2001 for the construction of the antenna, which is divided into 3 time periods:

• Start of the work: from 12th December 2000 to 26th February 2001, consumption: (44 kW h) × (65 working days) × (10 h) = 28 600 kW h.

• From 26th February 2001 to 17th July 2001, consumption: (280 kW h) × (121 working days) × (10 h) = 338 800 kW h.

• End of the work: from 17th July 2001 to 13th November 2001, consumption: (44 kW h) × (102 working days) × (10 h) = 44 880 kW h.

These consumptions were subsequently divided over the antenna's 50 years of life.

2.4.2 Power plant. The New Norcia's power plant site acts both as a connection to the grid and as a backup in the event of power failure from the main network and includes two diesel generators, sixty $LiFePO_4$ batteries and two modular UPS converters. Due to the lack of information regarding the masses of different materials included in such components, it was not possible to create LCA processes with primary data. Instead, the best corresponding items with the related masses have been identified in the Ecoinvent 3.8 database with the support of ESA's experts. Furthermore, due to the absence of data regarding the nation of departure of $LiFePO_4$ batteries, the market process was selected on SimaPro instead of the transformation process. The quantities of these components, their characteristics, and the information regarding their transport to the site are summarised in Table 3.

2.4.3 Photovoltaic plant. Eight hundred and twenty photovoltaic panels arranged in five double rows compose the photovoltaic plant, contributing to the on-site production of electricity equal to 35% of the total. The panels are monocrystalline. The quantities of these components, their characteristics, and the information regarding their transport to the site are summarised in Table 3.

2.4.4 Electricity consumption and production. The station is supplied with electricity from the national grid, while about

Table 2 Antenna components and quantities

Sections	Components	Materials	Amount	Unit	Nation of departure	Departure site	Arrival site	Truck (km)	Boat (km)
Upper	Reflector base	Steel	120	t	Estonia	Tallinn	New Norcia	126	23 800
	Reflector panels	Aluminium	15	t	United States	Greenville	New Norcia	686	24 700
Middle	Structural components	Steel	450	t	Poland	Kluczbork	New Norcia	576	23 150
	Structural components	Concrete	150	t	Australia	Perth	New Norcia	126	—
	Counterweight	Concrete	70	m^3	Australia	Perth	New Norcia	126	—
Lower	Structural components	Concrete	1200	m^3	Australia	Perth	New Norcia	126	—
	Reinforcing components	Steel	150	t	Australia	Perth	New Norcia	126	—
	Miscellaneous parts	Steel	20	t	Australia	Perth	New Norcia	126	—

35% of the total is produced on site with photovoltaic panels in the photovoltaic plant. The power received by the station from the supplier is at 33 kV, but the transformers bring it down to 415 V for the operation of all facilities. For this study, the total energy consumption in a period of 12 months (September 2017–August 2018) equal to 1360 MW h year^{-1} was considered. This was the only period with available data on energy consumption for one entire year. Of this amount, the photovoltaic plant produced 470 MW h year^{-1} over the same period. Consequentially, only the difference (890 MW h year^{-1}) was officially purchased from the public electricity grid.

2.4.5 Fuel consumption. Through the backup system, the station can cope with sudden blackouts of electricity from the grid. Therefore, fuel is purchased to power the diesel generators and is transported by trucks from Perth to New Norcia. The diesel fuel consumption of the diesel generators is on average 10 000 litres per year.

2.4.6 Maintenance. Maintenance of all components is essential for maintaining their functionality and ensuring optimal performance. Maintenance mostly includes checking the functions, cleaning parts, and re-adjustment operations. However, the following components are replaced during the entire life cycle of the station:

- $LiFePO_4$ batteries are replaced every 10 years.
- Modular UPS transformers are replaced every 20 years.
- The photovoltaic panels are replaced every 25 years.

Furthermore, lubricating gearbox oil is used to allow normal operation of the antenna rotation and movement machinery. The average consumption of this lubricating oil is 50 L year^{-1}.

2.4.7 Disposal. The end-of-life assumptions were suggested directly by the ESA based on the recent disposal of a smaller antenna. Indeed, in December 2015, a 16 meter antenna based in Perth was decommissioned and sold to the Portuguese government.[26] Then, the reflector was dismantled into pieces and shipped over to the Azores where it was rebuilt. The electronic equipment was also removed and shipped over. The concrete structure was scrapped, while the ground was restored to its original condition. The company that demolished the pedestal separated the steel from the concrete, and both were recycled. A crushing machine separated the concrete, and the resulting concrete pieces were used as substructure for roads and other constructions. Therefore, also in this case study, most of the materials and components of the station were directed to the recycling process. Components such as exhausted batteries and a small percentage of the non-recyclable materials of the photovoltaic panels have been directed to different disposal processes after a careful study of the end of life (*i.e.*, pyrolysis and landfill). Three disposal scenarios were therefore created: (i) recycling, (ii) incineration and (iii) landfill, where the percentages of waste sent to these 3 processes were divided according to specific national data for the Australian (scenario 0) and Spanish (scenario B) scenarios.[27,28] Furthermore, specifically, the disposal scenario (both Spanish and Australian) was modelled taking as reference the European LIFE project "Full Recovery End of Life Photovoltaic (FRELP)", considering that 90% of the materials comprising the photovoltaic panels are recycled and the remaining 10% is sent to landfill.[29]

2.5 LCIA method

The ReCiPe (2016) method with the hierarchist perspective (H) version was used to assess the potential environmental impacts deriving from the upstream, core and downstream processes.

Table 3 Power and photovoltaic plant components and values

Components	Amount (power)	Unit (power)	Nation of departure	Departure site	Arrival site	Truck (km)	Boat (km)	Amount (mass)	Unit (mass)
Diesel generators	520	kW	Germany	Augsburg	New Norcia	900	21 850	7650	kg
Modular UPS transformers	300 (if necessary, it can be extended to 480)	kW	Australia	Perth	New Norcia	126	—	1100	kg
$LiFePO_4$ batteries	—	—	—	—	New Norcia	—	—	6.5	kg
Photovoltaic panels	470	MW h^{-1} year^{-1}	South Korea	Seoul	New Norcia	175	9260	17	kg

ReCiPe 2016 is a harmonized life cycle impact assessment (LCIA) method that translates emissions and resource extractions into environmental impact scores. It was developed through cooperation between RIVM, Radboud University Nijmegen, Leiden University, and PRé Sustainability. The method implements human health, ecosystem quality, and resource scarcity as three areas of protection. It provides characterisation factors that are representative of the global scale and includes 17 midpoint impact categories. ReCiPe 2016 also expanded the number of environmental interventions and added impacts of water use on human health, impacts of water use and climate change on freshwater ecosystems, and impacts of water use and tropospheric ozone formation on terrestrial ecosystems as novel damage pathways.

The hierarchist perspective is one of the three cultural perspectives utilized in the ReCiPe 2016 LCIA method. These perspectives represent a set of choices for issues like time or expectations so that proper management or future technology development can avoid future damage. The hierarchist perspective is often considered to be the default model. It represents a consensus model, as often encountered in scientific models. This perspective takes a balanced view, neither overly optimistic nor pessimistic, and is based on the assumption that societal consensus and scientific models will guide us towards sustainable solutions.

3 Results

In this case study, it was decided to report the characterized and normalized results both at the midpoint and endpoint levels. To clearly understand the distribution of environmental impacts of the New Norcia plant, different inventory categories have been created: (I) "station", composed of the raw materials and the energy used for their manufacturing of terminal, power plant and photovoltaic panels, (II) "energy", which includes the consumption of electricity and fuel needed to power the space tracking station operations, (III) "transports", which includes the ships and trucks used to transport raw materials and tracking station components, (IV) "maintenance", which includes components that may be substituted, and (V) "disposal", which includes all the processes for the disposal of waste from the decommissioning of the space tracking station.

Fig. 3 displays the flowchart of the whole LCA study where the line thickness represents the relative contribution to impacts from the different processes. All acronyms used in figures, which refer to midpoint and endpoint indicators, are reported in Section S2 of the ESI.†

3.1 Endpoint results of scenario 0

The ReCiPe method provides results both at midpoint and endpoint levels. Results in this section are reported using the three endpoints' indicators assessing damage to human health, ecosystems and resources.

As impacts related to different midpoint or endpoint categories are each presented with its own unit of measure, a normalization step is needed to be able to compare them. Normalization allows comparison between different impact categories by transforming each category's impact value into a unified unit of measure, representing impacts relatively to a predefined reference value. The reference value utilised by the applied ReCiPe method is the yearly average impact of a European citizen and the corresponding unit of measure is the ecopoint (pt).

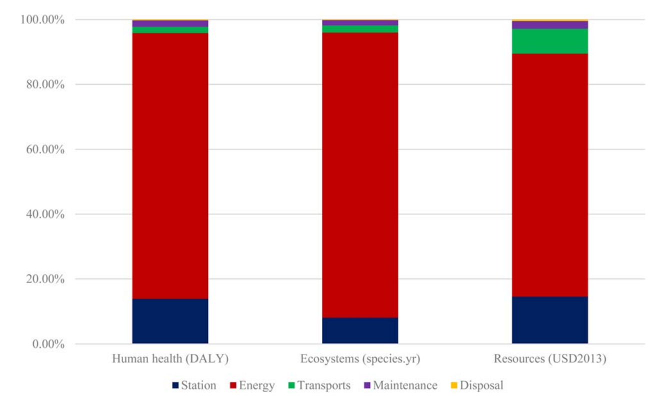

Fig. 4 Scenario 0: endpoint characterization results.

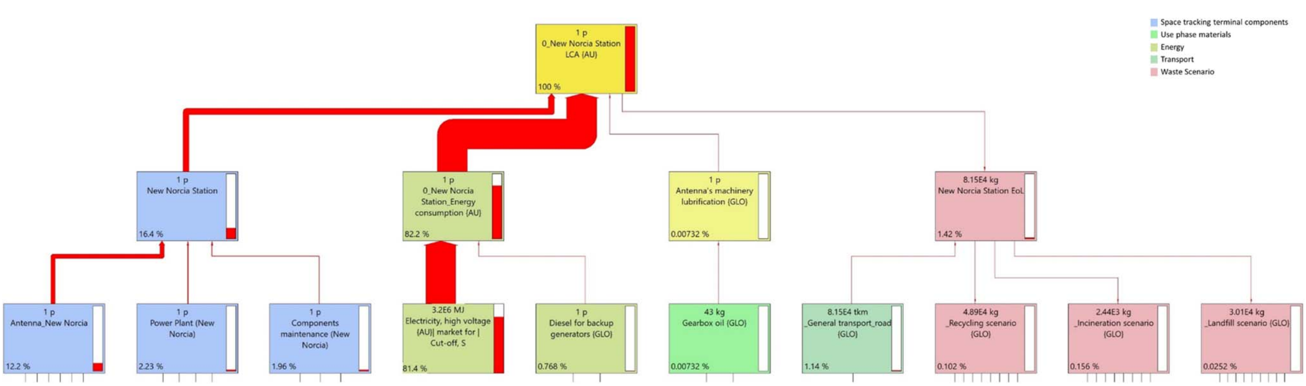

Fig. 3 New Norcia life cycle assessment flowchart including only the 3 upper levels of the model. The red lines below the last reported level correspond to further sub-categories. The thickness represents the relative contribution to the environmental impacts from the different processes. All elements contributing to the flowchart are reported in ESI Table 1.†

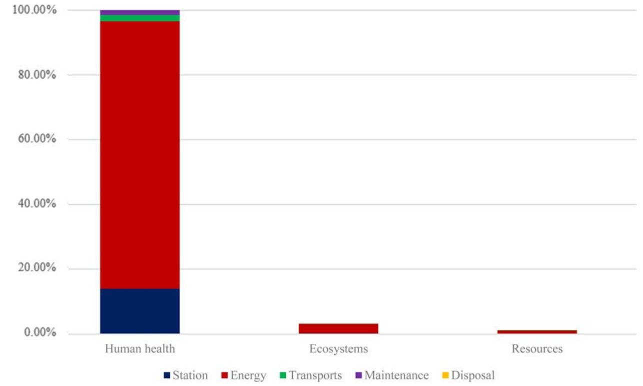

Fig. 5 Scenario 0: endpoint normalization results.

Endpoint results reported in Fig. 4 provide an overview of the damage generated by impacts caused by the different life cycle processes of New Norcia. In Fig. 4, "energy" is the most impacting inventory category with more than 74% of total damage for each endpoint (82% for the human health, 88% for the ecosystems and 75% for the resources). Otherwise, Fig. 5, related to normalized results, shows that the "human health" endpoint is the most impacted mainly due to the "energy" category and partially for the "station" category.

3.2 Midpoint results of scenario 0

Midpoint results are more precise than endpoint results as fewer aggregations took place. Relative characterization midpoint results of scenario 0 are reported to 100% for each impact category, as shown in Fig. 6. As anticipated by the endpoint results, "energy" is the most impacting inventory category for all impact categories. However, for the categories "ionizing radiation", "terrestrial ecotoxicity" and "mineral resource scarcity", a relevant percentage of impact is also caused by other inventory categories, such as the "station", the "transports" and the "maintenance" inventory categories.

Specifically, the ionizing radiation characterization midpoint results are driven by the "station" and the "maintenance" inventory categories, each contributing approximately 64% and 13% to the total impact. This is due to the type and quantity of minerals extracted for the construction and maintenance of most photovoltaic panels. In addition, concrete is the most impactful material used in the construction of the antenna, primarily due to the large quantity required. The terrestrial ecotoxicity characterization midpoint results are instead caused by "station", "transport" and "maintenance" that contribute approximately 36%, 18% and 23%, respectively, to the total impact. This is also caused by the type and quantity of minerals extracted for the construction and maintenance of photovoltaic panels and diesel generators. It can be noted that the mineral resource scarcity characterization midpoint results are due to the "station" inventory category that has an impact of approximately 84%. Also, in this case, this is caused by the type and quantity of minerals used in the construction of all components. Indeed, the most impacting elements are concrete, diesel generators, transformers, and photovoltaic panels. Furthermore, in Fig. 7, the normalized results are reported, which denote a predominance in impacts to "freshwater eutrophication", "freshwater ecotoxicity", "marine ecotoxicity" and "human carcinogenic toxicity", where the "energy" and "station" inventory categories are the main cause of impacts.

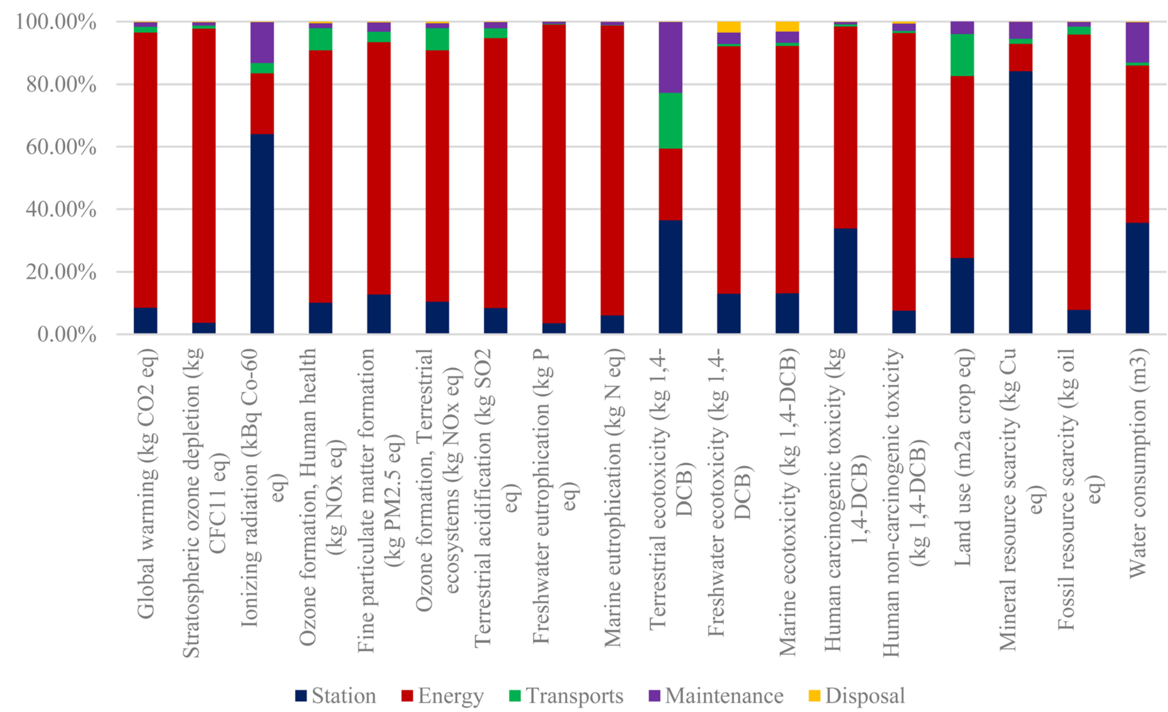

Fig. 6 Scenario 0: midpoint characterization results.

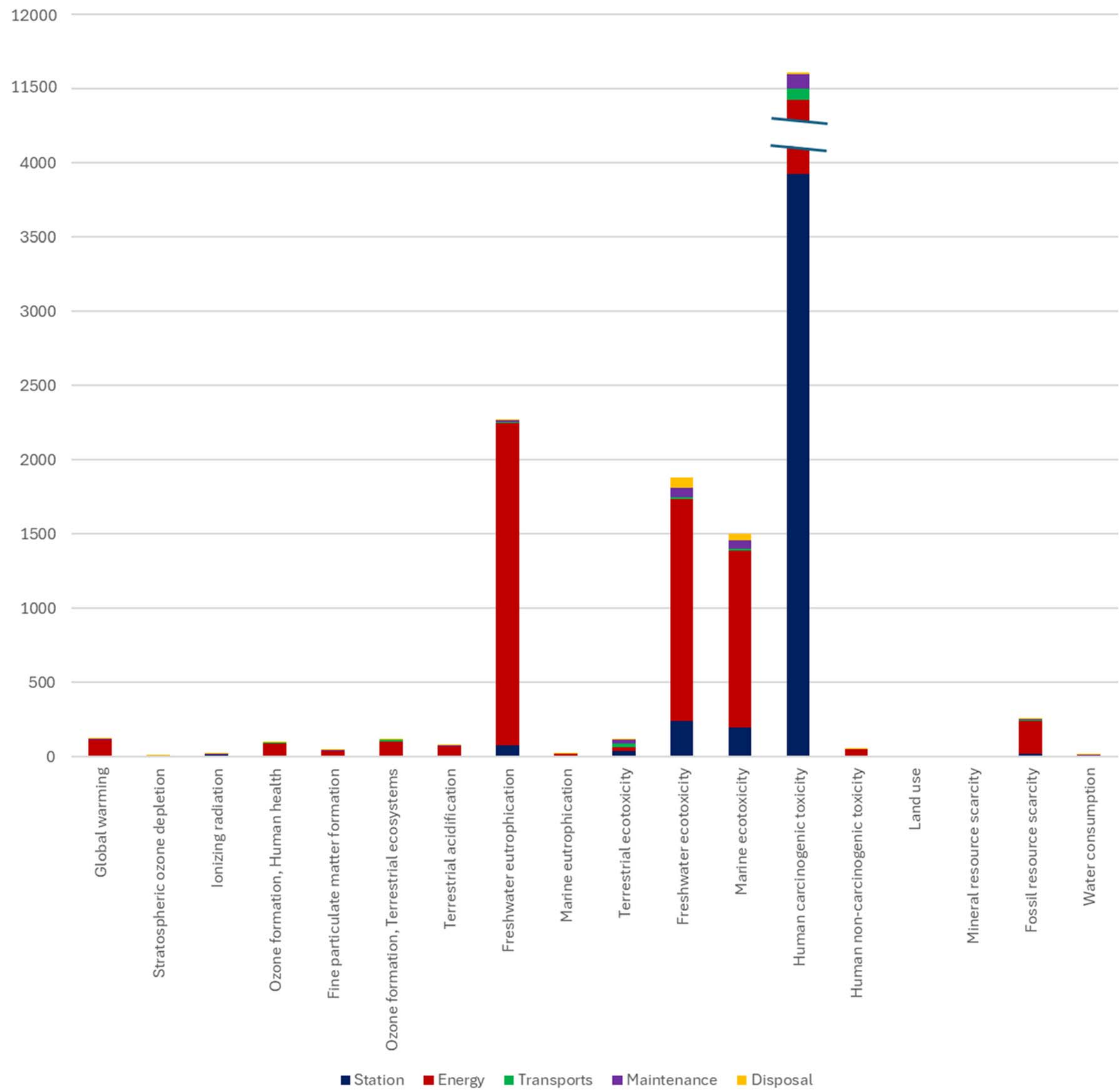

Fig. 7 Scenario 0: midpoint normalization results expressed in eco-points.

3.3 Endpoint results of the comparison scenario

"Scenario 0", which represents the actual New Norcia case study, as presented in the previous sections, has been compared with other two scenarios:

- Scenario A: scenario 0 without photovoltaic panels to produce electricity on-site and without batteries for energy storage. Accordingly, the "maintenance" inventory category related to photovoltaic panels and batteries is not included in this scenario. The purpose was to observe the difference in impacts resulting from the absence of photovoltaic panels utilised in scenario 0.

- Scenario B: a plant like New Norcia located in Cebreros (E) without photovoltaic panels and batteries. In this scenario, both the transport of raw materials for construction of the plant and the utilized energy mix are related to the Spanish context. Furthermore, also in this scenario, the "maintenance" inventory category related to photovoltaic panels and batteries is not included. This scenario has been modelled to understand how the environmental impacts might change according to the plant geographical location. A special focus is also dedicated to the energy mix, since the Australian energy mix is mainly driven by coal, which is a CO_2eq. intensive emitter, while the Spanish one is a more eco-friendlier energy mix, which is mainly driven by renewable energy. For more information on the changes made to the New Norcia model, refer to Table 1 and Fig. 2 within ESI S1.†

The different scenarios have been compared by means of characterization and normalisation results, as presented in the sections below.

As reported in Fig. 8, "energy" is the most impacting inventory category in all scenarios. The most impacting scenario for all the three endpoints is scenario A, *i.e.*, the scenario without photovoltaic panels and batteries located in Australia. Indeed, photovoltaic panels help saving 470 MW h of energy per year, which decreases the overall environmental impacts compared to the scenario without panels. Furthermore, "raw materials",

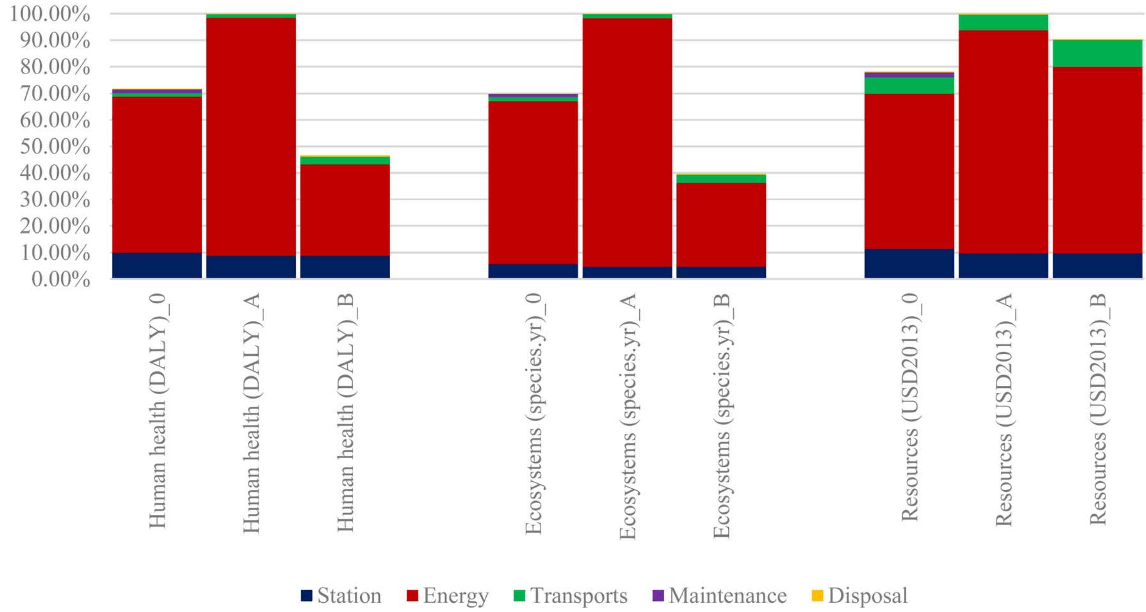

Fig. 8 Comparison of the three scenarios: endpoint characterization results.

"end of life" and "maintenance" of the panels have a lower impact compared to "energy", as shown in Fig. 3. Scenario 0 has lower impacts than scenario A, but it is not the best scenario. Indeed, scenario B, thanks to the Spanish energy mix, which is more oriented towards renewable energies than the Australian one, is the less impactful scenario. However, due to some components of the Spanish energy mix related to the use of nuclear energy, which will be further discussed later, scenario B has greater impacts concerning endpoint resources. However, once normalized, this resource endpoint does not have significant impacts, as reported in Fig. 9.

Additionally, Fig. 9 reports the normalized impacts of the three scenarios, where human health presents the most impacted endpoint for all three scenarios and scenario A is the most impactful scenario.

3.4 Midpoint results of the comparison scenario

Relative characterization results of the alternative scenarios are reported for each midpoints' impact category, where 100% is assigned to the most impactful scenario for each individual midpoint. As anticipated by endpoint results, "energy" is the most impacting inventory category for several categories in the

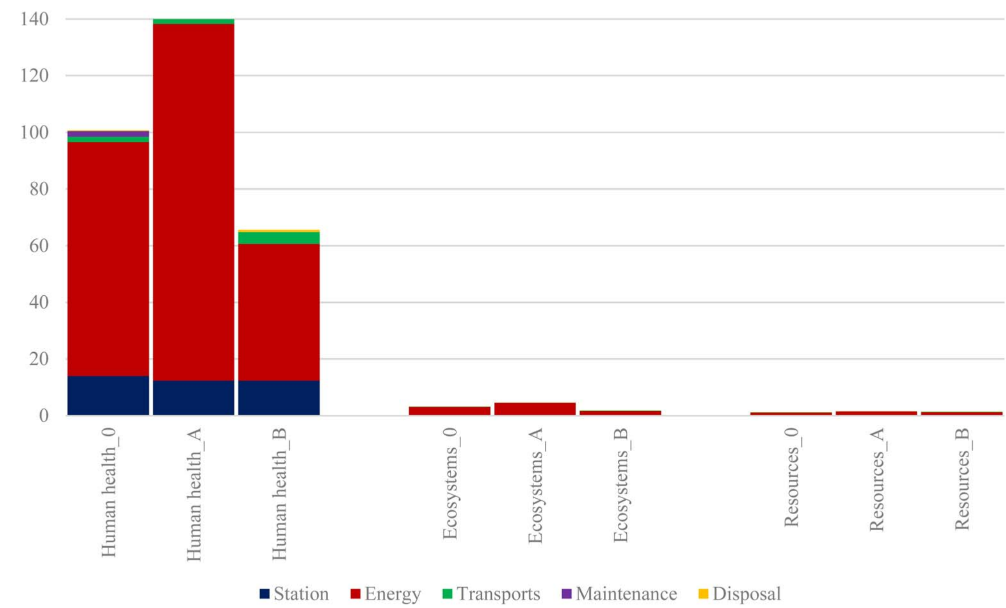

Fig. 9 Comparison of the three scenarios: endpoint normalization results expressed in eco-points.

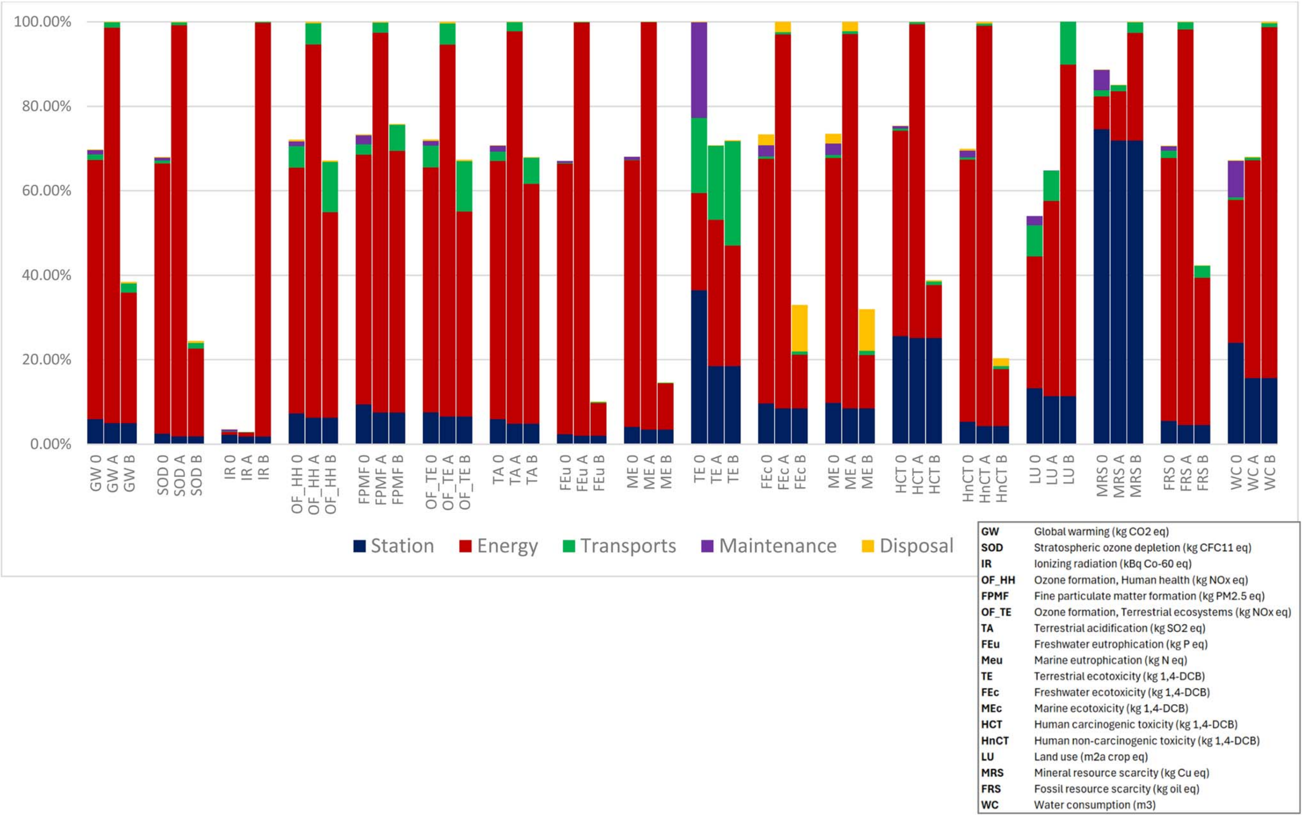

Fig. 10 Comparison of the alternative scenarios: midpoint characterization results.

three scenarios. However, it should be noted that in the categories "terrestrial ecotoxicity", "human carcinogenic toxicity" and "mineral resource scarcity" a relevant percentage of impact is due to other inventory categories such as "station", "transports" and "maintenance", as displayed in Fig. 10 and further discussed in the following sections. Specifically, for the terrestrial ecotoxicity midpoint results, scenario 0, that is the most impactful, is mainly driven by the "station" (approximately 36% of the value), followed by the "energy" and "maintenance" categories which contribute approximately 23% to the total impact and by the "transport" inventory category with 18% to the total impact. In addition, the "energy" inventory category of scenarios A and B contribute approximately 35% and 28% to the total impact of this indicator. The differences between scenarios 0, A and B are mainly due to the absence of photovoltaic panels and batteries in the last two scenarios. In this case, the causes of the impacts are also due to the type and quantity of minerals extracted for the construction and replacement of photovoltaic panels and diesel generators. The human carcinogenic toxicity midpoint results are partially driven by the "station" for all three scenarios with approximately 26% of the total impact. Lastly, in scenarios 0, A and B, the midpoint of mineral resource scarcity is mainly driven by the "station" inventory category which accounts for 72% of the total impact in the case of A and B scenarios and around 75% in scenario 0. Due to the absence of photovoltaic panels and batteries in scenarios A and B, the impacts on resource consumption are lower when compared to scenario 0. In any case, in this category, all three scenarios have a considerable impact due to the raw materials used for various components of the New Norcia or Cebreros station. Indeed, in scenario 0, the most impacting elements are concrete, diesel generators, transformers, and photovoltaic panels, while in scenarios A and B photovoltaic panels are not considered. Another important point is that only the midpoints "terrestrial ecotoxicity" and "mineral resource scarcity" of scenario 0 are more impactful than scenario A. This is due to the raw materials necessary for the construction of the photovoltaic panels and other components of the station. Lastly, due to both the Spanish energy mix and the construction materials, scenario B is worse than scenario A in "ionizing radiation", "terrestrial ecotoxicity", "land use", "mineral resource scarcity" and "water consumption". As regards the midpoints "ionizing radiation" and "mineral resource scarcity", scenario B is worse, especially for the first midpoint due to two different components within the Ecoinvent process that models the Spanish energy mix. Specifically, the tailing component, from uranium milling (see ESI S1†), governs almost 93% of the energy impact deriving from the midpoint "ionizing radiation". While the component uranium ore, as the uranium mine operation, is instead the cause of the worst environmental performance of scenario B for the "mineral resource scarcity" midpoint. Furthermore, in Fig. 11, it is possible to observe the normalized results for the three compared scenarios. Normalized results show a predominance in impacts to "freshwater eutrophication", "freshwater ecotoxicity", "marine ecotoxicity" and "human carcinogenic toxicity". It is important to note that the "terrestrial ecotoxicity" and "mineral resource scarcity" impact categories mentioned above have a negligible impact once the data are normalized.

4 Discussion of the results

In the next sections, a discussion of the single score results for the three scenarios, (0) New Norcia, (A) New Norcia without photovoltaic panels and batteries and (B) plant like New Norcia without photovoltaic panels and batteries located in Cebreros (E), is provided. Initially, the single score results for scenario 0 are presented, followed by the comparison of the single score results for the three scenarios (0, A and B). The ReCiPe method (2016) has been used for the single score estimation. As previously reported, midpoint indicators focus on single

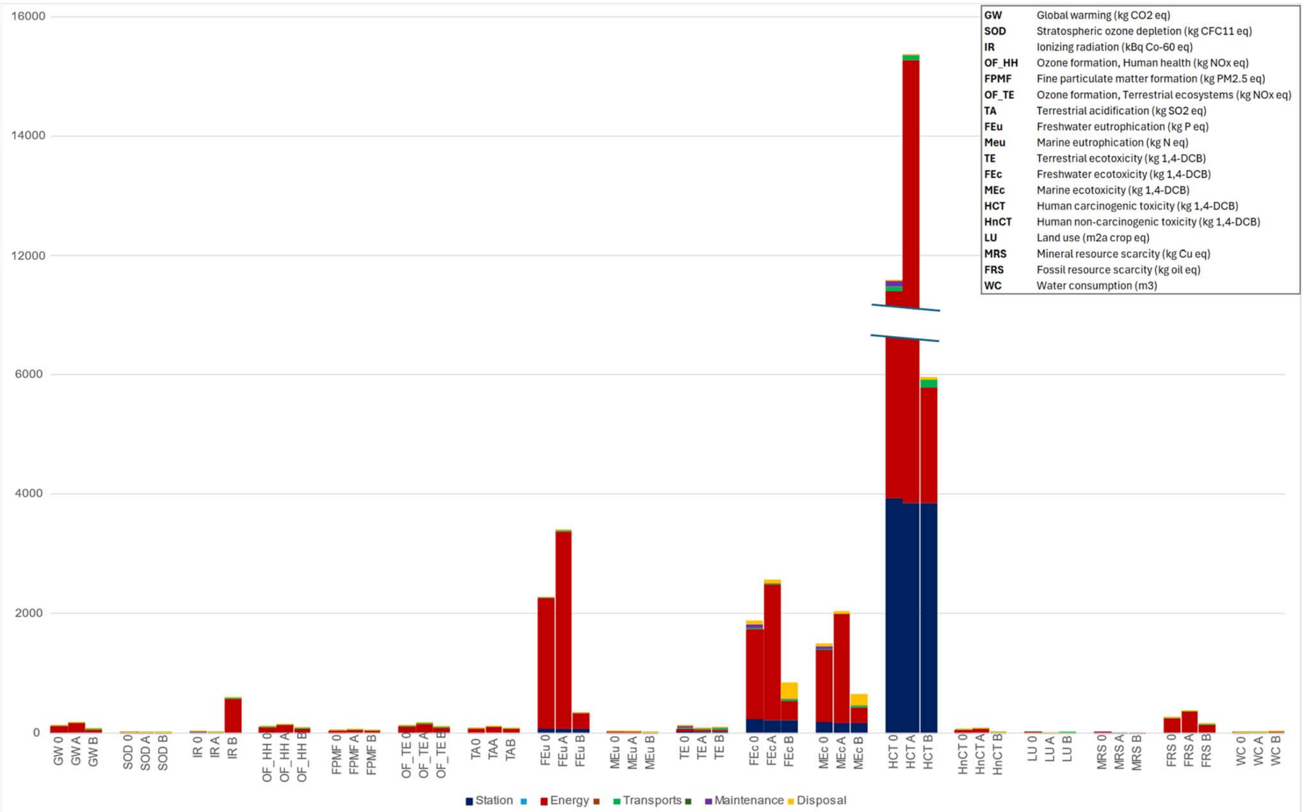

Fig. 11 Comparison of the alternative scenarios: midpoint normalization results expressed in eco-points.

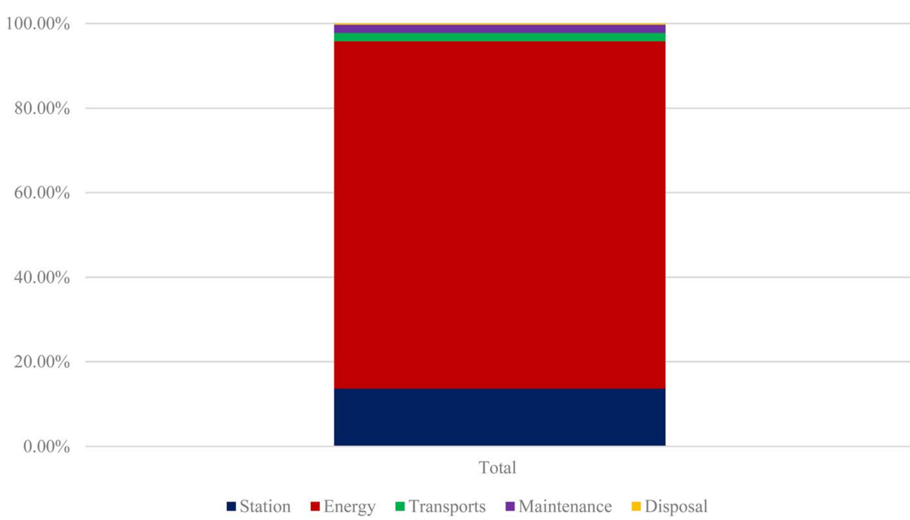

Fig. 12 Scenario 0: single score results.

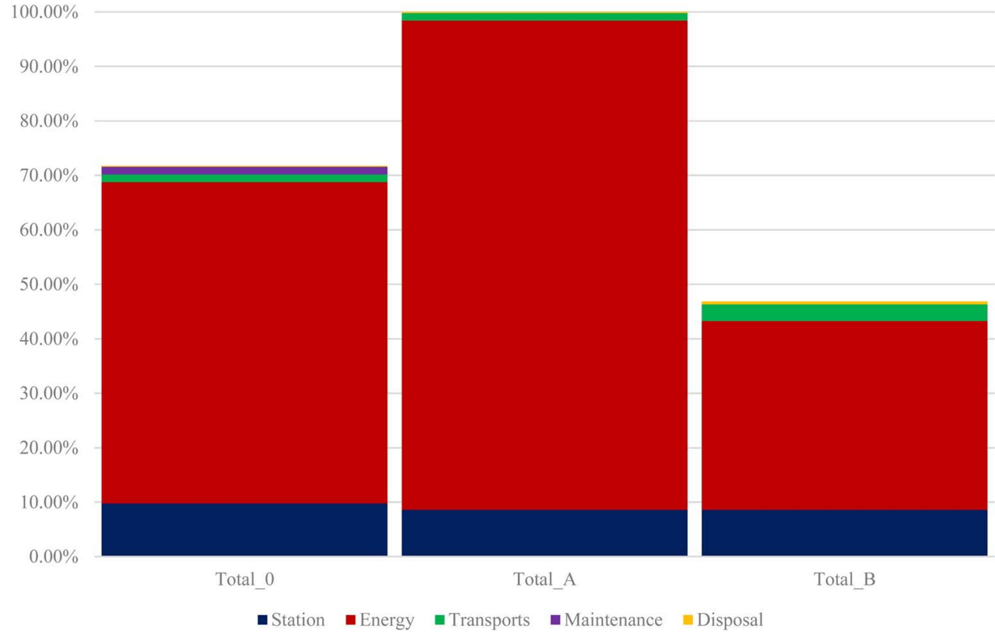

Fig. 13 Comparison of the alternative scenarios based on the single score results.

environmental problems; otherwise, endpoint indicators show the environmental impact on three higher aggregation levels. Finally, the single score is the result of further aggregation of the 3 endpoints into a single indicator.

4.1 Life cycle interpretation of scenario 0

The single score results obtained with the ReCiPe method for scenario 0 are reported in Fig. 12, where it is possible to see that the "energy" inventory category is the most impactful. It should be noted that this inventory category includes 1.36 GW h year^{-1} of high voltage electricity purchased from the national grid and 10 000 L year^{-1} of diesel used to run the backup diesel generators. The total contribution of "energy" is, indeed, equal to approximately 82% of the total. This is primarily due to the large amount of electricity purchased each year, followed by the liters of diesel burned annually for energy production.

The other inventory category that exceeds 14% of the total impacts is the "station". As displayed in Fig. 12, the impacts of the "station" involve 1/7 of the total impacts. These impacts are mainly caused by raw materials and components used for the construction of the entire station which have negligible impacts if the entire life cycle of the plant is considered. The same holds for impacts associated with the "transport", "maintenance" and "disposal" inventory categories, which are mostly negligible.

4.2 Life cycle interpretation of scenarios 0, A and B

From the single score results obtained with the ReCiPe method shown in Fig. 13, it is clear how impacts caused by the "energy" category are the highest for all three scenarios.

According to Fig. 13, the impacts due to the "energy" inventory category have a value of 60% for scenario 0, 90% for scenario A and 35% for scenario B. This great difference (+30%) between scenarios 0 and A is due to the absence of photovoltaic panels and batteries in this last scenario. Indeed, thanks to the panels, being able to produce 470 MW h of electricity on site of the total annual consumption of 1360 MW h contributes to the reduction of the purchase of electricity from the grid by about 35%. This also has direct benefits for the environment since it significantly reduces the purchase of energy that is produced using, for example, fossil sources. Otherwise, an eco-friendlier energy mix like the Spanish one (scenario B) involves a 55% decrease in the impact derived from the energy compared to scenario A. Even if scenario B has greater impacts on the transport of construction materials, thanks to a less impacting energy mix, it manages to result in a scenario with fewer environmental impacts at the single score level. All other differences in comparison with scenario 0 are always connected to the absence of photovoltaic panels and batteries in scenarios A and B. Indeed, in scenario 0, the "maintenance" inventory category affects +1.39% as compared to scenarios A and B. The reduced impacts of this inventory category in scenarios A and B are obviously due to the absence of components installed which require maintenance during the life cycle of the station. Moreover, the "transport" does not show appreciable differences, settling on an impact value of approximately 1.40% for scenarios 0 and A and 3% for scenario B. Finally, the "disposal" inventory category has an impact of approximately 0.20% for the first two scenarios and 0.54% for the last one.

4.3 Future improvements & eco-design applications

Due to the high contribution of electricity consumption, the largest investments in terms of reducing environmental impacts are to be made in the energy inventory category. Since the type of a country's electricity mix is a factor that cannot be directly controlled by a company or institution such as the ESA, the main solution with immediate and clear results is to carefully choose the country to build the space ground tracking station. Favouring countries whose electricity mix is more oriented towards the use of renewables as opposed to fossil fuels helps reduce the impact considerably, and not only in terms of CO_2eq. Unfortunately, ESA's choice of sites to building space ground tracking stations is limited to countries with low light pollution and as little anthropogenic interference as possible in order to maximise the technical functionality of these installations. Although this may be a limiting factor, as in the case of the New Norcia station, it is possible to install technologies in the vicinity of the installations that allow energy to be produced on-site, such as photovoltaic panels or wind turbines, and, consequently, reduce the energy supply from the national grid.

On the other hand, the ESA can directly influence the types and quantities of materials used in the construction of ground-based space tracking stations. Within the limits of what is possible from an engineering point of view and related to the functionality of the facility, reducing the mass of the entire structure consequently reduces the environmental impact as the latter is closely linked to the quantities of raw materials that are extracted and subsequently processed to produce the various components of a tracking station. Furthermore, it is possible to specifically investigate the composition of the materials used for the construction of these plants in order to identify the best possible solution to be adopted for future constructions. Lastly, one of the main problems that the ESA will have to face in the coming years concerns critical raw materials (CRMs). CRMs are those raw materials that are economically and strategically important for the European economy but have a high risk associated with their supply. As CRMs are crucial for the development of renewable technologies such as PV panels, their careful management will be crucial in order to reduce environmental impacts due to the construction of new PV panels. The extraction of rare earths entails very high impacts that will need to be contained. For this reason, the ESA plans to improve the energy efficiency of the panels by reducing the amount of electricity fed back into the grid in order to optimise the electricity produced and consumed on site and thus the number of PV panels needed for the space ground tracking stations.

5 Conclusions

This paper allowed us to understand how sustainability and sustainable development are becoming important reference points for space agencies. Indeed, in this paper, a screening LCA study was proposed with the aim of evaluating the environmental impacts of the satellite tracking ground station located in New Norcia (AU) that can be used to compare similar future constructions. Some assumptions, simplifications, and approximations were made due to the lack of primary data. To enhance the quality of the presented results, an uncertainty assessment and an organizational LCA could be performed; however, these aspects are outside the scope of this study.

The assessment showed that among all the components of the installation, the consumption of electricity from the electricity grid causes more than 82% of the environmental impacts overall, as can be seen in Fig. 12. To better understand how impacts of electricity might change according to in-house production and geographical location two alternative plausible scenarios were created: (i) scenario A, which is identical to scenario 0 without photovoltaic panels and batteries and (ii) scenario B, which consists of a plant like New Norcia without photovoltaic panels and batteries located in Cebreros (E). In these scenarios, both the transport of various raw materials for the construction of the plant and the energy mix are related to the Spanish context.

The comparison between scenario 0 and scenario A showed that the energy produced by photovoltaic panels can reduce environmental impacts by 30%. In scenario 0, the most relevant impacts evaluated through the normalized midpoints are always caused by the "energy" inventory category because about 70% of the energy used by the antenna is purchased by the Australian grid which has an energy mix mainly based on non-renewable sources such as coal.[30] However, these impacts can be considered as indirect since the ESA is not directly responsible for them. The use of photovoltaic panels is therefore highly recommended because impacts caused by the production of the panels are negligible compared with impacts caused by energy production.

Therefore, on-site energy production is the optimal solution to reduce the impacts caused by energy consumption considering the Australian energy mix.

A comparison of impacts caused by scenario 0 and scenario B show that utilising a less fossil fuel-oriented energy mix can allow the ESA to decrease their environmental footprint. Indeed, as it can be observed in Fig. 10, the Spanish energy mix, although not among the least impacting energy mixes in the world, could reduce CO_2eq. emissions by more than 60% compared to scenario A, *i.e.* equivalent to power plants without photovoltaic panels and by almost 40% compared to scenario 0 with photovoltaic panels.

One conclusive consideration is that one of the most relevant problems related to photovoltaic panels is associated with critical raw materials (CRMs). CRMs are those commodities that are economically and strategically important for the European economy but have a high risk associated with their supply. To meet future energy demand through renewable energies, the demand for photovoltaic panels and other renewable energies will increase. As a result, the consumption of raw materials needed to manufacture these technologies is expected to dramatically increase over the coming decades. For these reasons, the most immediate solution to reduce the environmental impacts due to the construction of new photovoltaic panels and to reduce the costs of their purchase is to recycle their components when possible. The ESA also plans to improve the energy efficiency of the panels. About 20% of electricity is put back into the electricity grid because there are no batteries connected to the panels for energy storage.

Data availability

The data used in this article have been already included in Section 2.4 Inventory data. The access to the SimaPro Project which generated the results presented in the article can be made available upon request from the authors.

Conflicts of interest

There are no conflicts to declare.

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