Final report

GreenSat – Executive Summary Report

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EXECUTIVE SUMMARY

Due to the harsh nature of outer space, stringent requirements and performance are required from space systems. Thanks to evolving environmental awareness and the building up of a knowledge base at ESA, the environmental impact of space activities on Earth is progressively taking a bigger role. Through the GreenSat project, ESA wants to evolve from assessment to reduction of environmental impact through redesign of an existing satellite mission. With the GreenSat project ESA wants to check the feasibility of implementing ecodesign in the development of space missions. The main objectives for doing an LCA in GreenSat are:

- to identify environmental hot spots of the mission, which is an important starting point to look for ecodesign options;
- to quantify the environmental impact of the mission, to understand the impacts and the sources, which is a baseline to benchmark the environmental impact of the ecodesigned GreenSat mission and which allows to assess the environmental impact reduction.

PROBA (PRoject for On-Board Autonomy) is a family of small satellites developed for the European Space Agency by QinetiQ Space. The PROBA-Vegetation (PROBA-V) mission, an earth observation mission, was selected as a continuation of the Vegetation programme. The main payload of the PROBA-V satellite is the Vegetation Instrument. The PROBA-V ground segment is composed of the mission control centre (MCC) at ESA ground station in Redu, monitoring and controlling the satellite bus and payloads. Additional ground stations such as Kiruna, Inuvik, and Fairbanks, are used for additional data downlink or critical operations. The user segment is operated by VITO, where the VGT-P data is processed, the final products (from raw to level-3) are generated and archived, and payload calibration is performed. The satellite was launched in May 2013 as a secondary payload on a Vega launch vehicle and is fully operational since then.

In work package 1 (TN1, VITO, 2018a), a Life Cycle Assessment (LCA) was performed for the PROBA-V mission, to identify the environmental hotspots of the mission. The functional unit is defined conform the space system LCA guidelines: “one space mission in fulfilment of the mission's requirements”. The PROBA-V LCA includes all activities in the space and ground segment, the launch segment is excluded:

- *Space segment*: composed of PROBA-V platform with Vegetation instrument and additional technology demonstration payloads;
- *Launch segment*: capable of placing the PROBA-V satellite into the selected orbit;
- *Ground segment*: for controlling and monitoring the satellite and archiving the Vegetation instrument data at Level 0, including the mission flight dynamics teams and including the user segment for processing the forwarded Level 0 (unprocessed) data up to Level 3 (variables mapped on a grid).

It is a cradle-to-grave LCA-study, including research, testing, raw material acquisition, manufacturing, use and end-of-life.

The initial LCA of the PROBA-V is performed in 2 iterations, i.e. in a first iteration a hybrid IO-LCA is done followed by an LCA according to ESA LCA guidelines in a second iteration. The only difference between iteration 1 and 2 is the modelling of the environmental impact of manhours needed during the mission’s life cycle. In iteration 1 manhours are modelled based on cost data. The environmental impact per manhour is taken from input output databases. Depending on i) the phase of the mission and ii) the type of manhours (QinetiQ, ESA, VITO) different sectors are used for the modelling. Iteration 2 starts from the actual number of manhours performed during the different phases of the PROBA-V mission. The environmental impact is based on data for energy use, travel, and infrastructure for QinetiQ, ESA (ground station) and VITO (data processing). The modelling of the satellite components is based on physical data in both iterations. Later in the project a third LCA-iteration is done to update the environmental profiles of the PROBA-V mission according to additional insights and data that were gained.

The life cycle impact assessment for PROBA-V is performed for the environmental impact categories and according to the defined LCIA methods as provided in the LCIA method in the ESA LCA database. Given the relevance of critical materials use in space applications, an additional 'impact category (Criticality – weighted)' that assesses the availability of raw materials, taking into account socio-economic constraints is defined.

Only minor changes occur between iteration 2 and 3. The environmental profiles presented are the final profiles resulting from iteration 3. The LCA identifies phase CD and E2 as the major contributors to the environmental impact of the mission. Their relative importance however is different, phase E2 is the phase with the largest impact (31-64% depending on the impact category, except for mineral resource depletion), followed by phase CD with a contribution ranging from 30 to 50% (except for mineral resource depletion, where CD accounts for 100% of the impact). Phase B generates 3 to 7% of the total impact and phase E1, 2 to 10% (not taking into account resource depletion). The impact of phase A is almost negligible.

The climate change impact of the PROBA-V mission (over a life time of 5 years) amounts to 1.629 ton CO_2-eq. This impact is mainly *energy-related*, as is the case for other impact categories. The impact of climate change, photochemical ozone formation, marine eutrophication and primary energy consumption (flow indicator) is mainly caused by the burning of fossil fuels for electricity production, transport or direct heating. The mining of coal and lignite has a large contribution to freshwater eutrophication. Ionizing radiation is originating from nuclear power production. Water consumption and particulate matter are mostly caused by electricity production in power plants. Other impact categories are related to *materials extraction and production* for the satellite components and infrastructure. This is the case for human toxicity non-cancer and cancer effects, acidification, freshwater and marine ecotoxicity, mineral resource depletion and metal depletion.

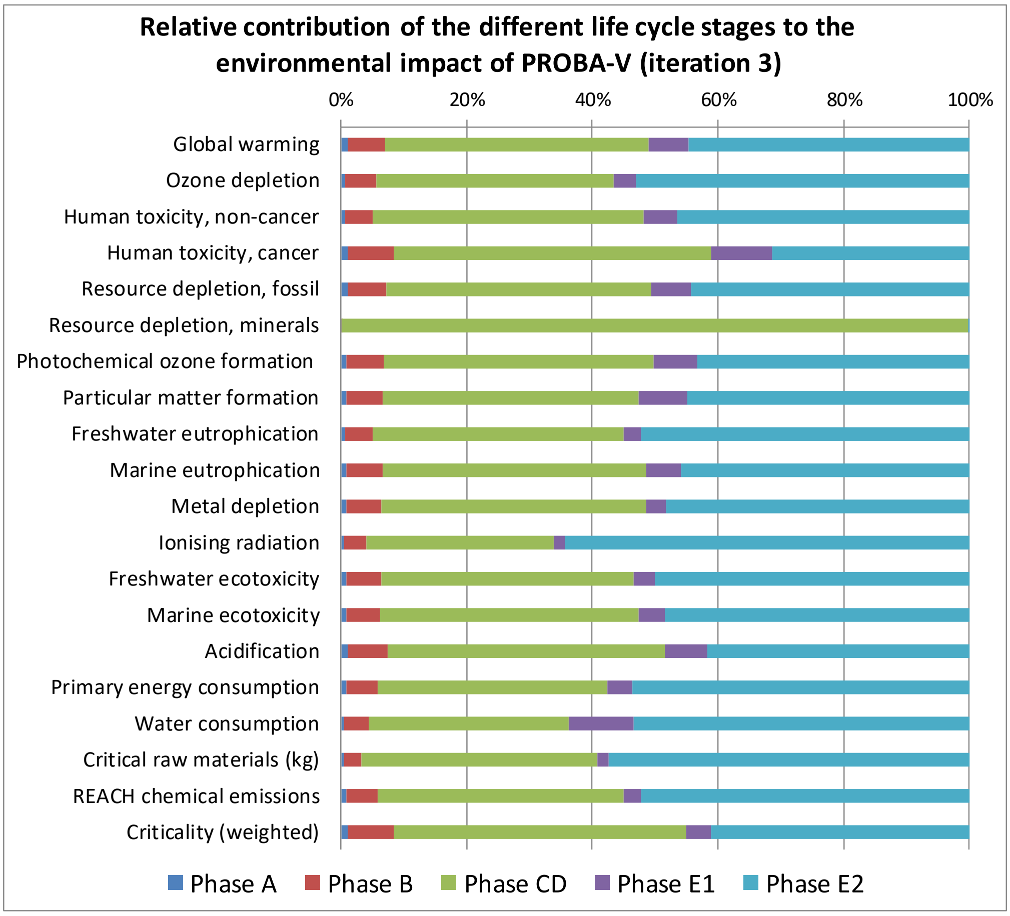

Figure 0.1: Environmental profile of the PROBA-V mission including infrastructure (excluding launch), according to iteration 3

The phase E2 impact is mainly caused by the *data processing* and is primarily coming from the production of the *electronics* e.g. servers and tape robots, from the *electricity consumption* and from the building *infrastructure*.

The impact of phase CD is divided over the impact of manhours and the impact of the satellite materials, testing and packaging. In almost all impact categories the impact of the *manhours* (consisting of energy use, infrastructure and travel) is larger than the impact of materials production. Only in the categories mineral resource depletion and critical raw materials, the impact of the materials for the satellite is larger than that of the manhours. The majority of the impact of manhours comes from the QinetiQ manhours, followed by the manhours performed by ESA. The manhours for the development of the Vegetation instrument is much less important and the impact of the manhours for the other components is negligible. The impact of the testing, split up into thermal testing in Toulouse and other testing, contributes to up to 9% of the total impact of the mission. The *thermal testing* generates an environmental impact mainly due to the production of the nitrogen and the transport of the satellite to the testing facility and only for a small share due to the electricity consumption. The environmental impact of the packaging of the satellite is negligible.
The *materials* for the satellite account for 1 to 20% of the total impact of the mission, with an outlier of 100% for mineral resource depletion. For energy related impact categories like climate change, fossil resource depletion and primary energy consumption the contribution is very small (few percentages). For ozone depletion, human toxicity non-cancer and freshwater eutrophication the impact of the materials is a bit higher (between 10-20%).

The LCA allowed to identify the environmental hotspots for the PROBA-V mission, which are most relevant to look at for the ecodesign exercise in the next study phase. Table 0.1 shows the hotspots per mission phase[1]. Some of the hotspots are related to the materials used in the satellite, but other hotspots relate to the manhours that are needed for the development, the operation and the data processing of the satellite and its payload. Particularly the energy consumption and to a lesser extent the infrastructure for manhour efforts in phase CD and phase E2 contribute largely to the environmental impact of the PROBA-V satellite. During the E2 phase the manhours performed by RSS for data reception and transmission (and more specifically, the energy use) are the main contributor together with the VITO data processing. Looking into the data processing at VITO, the electronics (servers) create a major environmental impact due to their production and electricity use, one of the reasons for this is the relatively short life span of the servers due to continuous technological improvements. During phase CD most of the impact is caused by the manhours at QinetiQ, followed by the manhours of ESA and of the contractor for developing the Vegetation instrument.

In figure 0.3, distinction is made between the different levels the hotspot can relate to: materials, equipment and components, manufacturing processes, system, management and programmatic issues, regulation. If an environmental hotspot contributes to more than 1 impact category/indicator, its environmental importance is higher.

As ESA has only little influence in the ground segment activities (e.g. energy use, data processing equipment), it is important to focus the ecodesign on technologies where ESA has impact on. Hotspots related to this can primarily be found in some components of the satellite (star tracker; solar cells in the power supply unit; wires in the harness; PTFE use in the ADPMS, harness and antennas; printed wiring boards in AOCS), and in the payload (Vegetation instrument and to a lesser extent the capacitors used in some technology demonstrators). The solar cells are one very important contributor to mineral resource depletion. Reducing the impact of this component can lead to a significant reduction for this impact category.

[1] A dark red colour indicates that more than half of the impact in a specific category is due to the item (e.g. production of a component, man-hours worked on a phase). Dark and light orange indicate that the item contributes for 25 - 50% and 10 - 25% of the impact, respectively. Yellow means that the item accounts for 2,5 to 10% of the impact in the specific category. Contributions of less than 2,5% are considered negligible and are not marked.

Impact category	Phase A	Phase B	Manp. QinetiQ - CD	Manp. ESA - CD	Manp. veget. instr.	Other manp. CD[2]	ADPMS	AOCS	Power supply	Veget. instr.	Other comp.[3]	Transp. comp., packag.	Testing	Phase E1	Manp. ESA,RSS, QinetiQ	Electr. (VITO)	Heating (VITO)	Building (VITO)	Batter. (VITO)	Servers (VITO)	Tape robots (VITO)
Global warming																					
Ozone depletion																					
Human toxicity, non-cancer																					
Human toxicity, cancer																					
Resource depletion, fossil																					
Resource depletion, minerals																					
Photochemical ozone formation																					
Particular matter formation																					
Freshwater eutrophication																					
Marine eutrophication																					
Metal depletion																					
Ionising radiation																					
Freshwater ecotoxicity																					
Marine ecotoxicity																					
Acidification																					
Primary energy consumption																					
Water consumption																					
Critical raw materials (kg)																					
REACH chemical emissions																					
Criticality (weighted)																					

Table 0.1: Overview hotspots

[2] Manpower on board SW, user segment, AOCS SW, structure, star trackers
[3] Other components: structure, thermal control, communications, harness, technology demonstrators

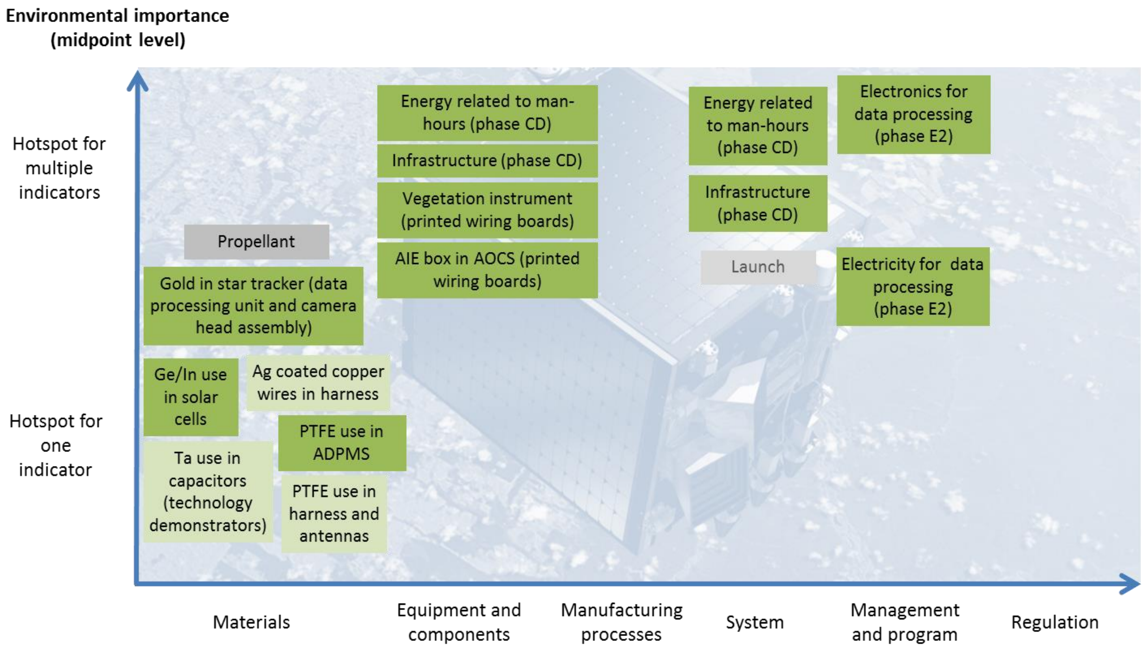

Figure 0.2: Hotspots of the PROBA-V mission

Prior to the eco-design, initial requirements are identified that would need to be adapted in case of a 'GreenSat' PROBA-V mission. In particular, the system should achieve equivalent function, meaning that the functional requirements should be almost all the same. As a consequence, functional requirements should not be significantly different. Design and operations requirements however could be significantly different.
The identified requirements for a GreenSat mission are that the mission is:

- a redesigned mission using ecodesign principles;
- compliant with the same or equivalent functional requirements.

A SWOT analysis is performed, based on the existing knowledge of the consortium partners about the regulatory context (VITO) and the space sector itself (QinetiQ). The SWOT addresses the opportunities and threats from regulatory aspects from three different policy levels:

1. Sectorial policy (related to the Intended Nationally Determined Contributions from countries that signed the COP21)
2. Product policy like the EU Ecodesign Directive
3. Substances (REACH)

In work package 2 (TN2; VITO, 2018b), starting from the identified environmental hotspots, ecodesign options for improving the environmental performance are defined. A two-step approach was followed to ensure maximum output:

- *External workshop* organized at ESA CDF premises, with a wider group of stakeholders;
- *Internal brainstorm* at QinetiQ Space, with experts specifically involved in the PROBA-V life cycle stages.

A long list of ecodesign options is generated for space missions in general and PROBA-V in particular. As only a limited number of ecodesign options can be further developed in GreenSat, a selection process is applied to the full list of options (see figure below).

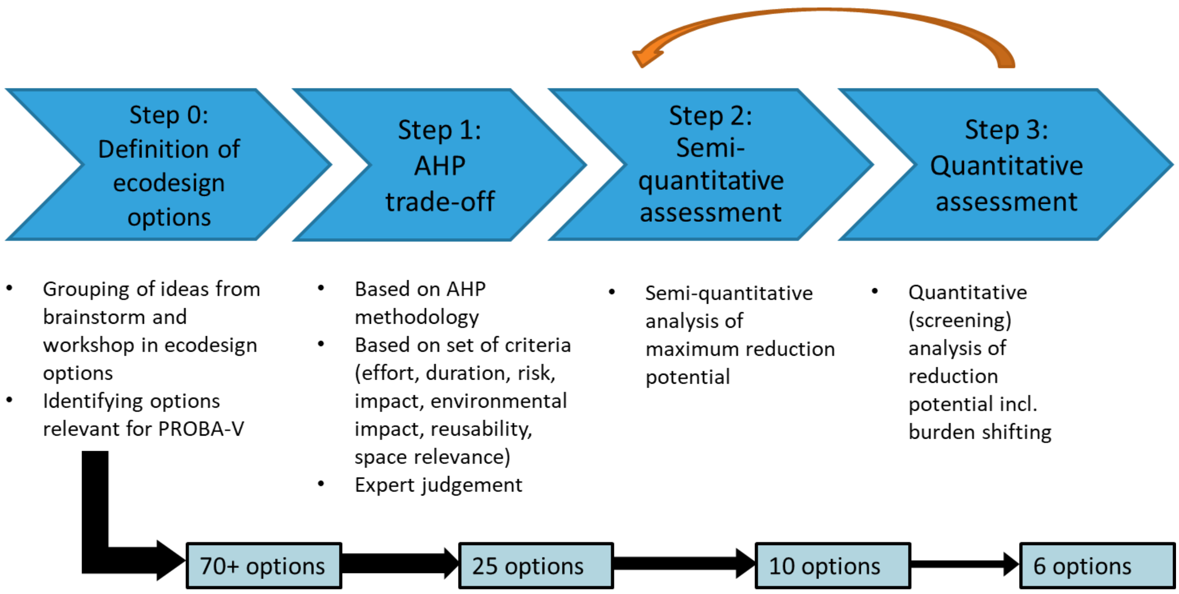

Figure 0.3: Selection process of ecodesign options

As a first step, an AHP trade-off was performed out of the 70+ identified options to select the 25 most promising ones, based on a consistent and commonly agreed weighting. This trade-off is based on the following criteria:

A. Solution implementation effort (cost, manhours, means)
B. Duration (time to market/launch)
C. Risk (feasibility, applicability, performance, availability of alternatives, flexibility)
D. Impact (operational cost)
E. Overall environmental impact
F. Reusability of the solution

An additional criterion is taken into account to identify the options that are 'space specific'. This is based on the ESA definition of 'space specific', referring to:

- Technologies for the space segment (including all equipment that will be flown, space environment considerations);
- Activities related to the space segment and their preparation, that differ from other ground activities (e.g. testing, transportation of equipment/satellite)[4];
- System Approach (e.g. level of autonomy, implementation of the use phase).

This criterion is not a fail or pass, but an additional one to make sure that in the final selection enough space-specific ecodesign options are present.

The Analytic Hierarchy Process (AHP) methodology is used for the trade-off. In a first step AHP allows to calculate weighting factors for the trade-off criteria, based on input from different stakeholders (brainstorm participants). In a next step, scores are assigned to each ecodesign option by VITO and QinetiQ, which leads to a final ranking of all ecodesign options. The top-25[5] ecodesign options including their scores are listed in the table below.

[4] For example: a telescope that needs to be on board a s/c has to be space qualified. The process of qualifying it for space is considered space specific.

[5] Due to the close relation of option 26 with option 13, we've included it as well in the table.

Option		Level	A	B	C	D	E	F	Score (%)	Space specific (ESA)
1	Not using PTFE but e.g. PE instead	1	5	5	5	3	5	4	92,1	x
2	Promote teleworking, use of teleconferencing	4	5	5	4,5	3	4	5	88,0	
3	More efficient on-ground data management	2	4	3	5	4	5	4	86,9	x
4	Use of long-heritage components	4	5	5	4	2	5	4	86,4	x
5	Use recycled Germanium	3	4	4	4	3	5	5	86,3	x
6	More efforts in early phases	5	4	4	4	3	5	5	86,3	
7	Green propellants	1	4	4	4	4	5	4	85,6	x
8	Reduce copper surface to be Ag coated	1	5	4	4	5	3	5	83,5	x
9	Flexible design	4	4	4	4	2,75	5	4	82,6	x
10	Renewable energy	4	4	3	4	3	5	4	81,2	
11	Reduce documentation	5	5	4	4	3	4	4	81,2	
12	Improve the efficiency of buildings	4	4	4	5	3	4	4	81,0	
13	System-level testing	4	4,5	5	3,5	3	4	4	79,8	x
14	Use of modular buildings for ground stations	4	4	5	4	3	4	4	79,6	
15	Recurrent platforms	4	4	3	4	3	5	3,5	79,6	x
16	Use of modular components	2	4	3	5	3	4	4	78,9	x
17	Si instead of Ge	1	4	5	5	1	4	4	78,2	x
18	Prolong electronics lifetime	2	3	4	4	3	5	3,5	78,1	x
19	Adopt PMI best practices and focus more on risk management	5	5	4	5	3	3	3,5	77,4	x
20	Laser/plasma surface treatment	3	4	5	5	3	3	4	77,4	x
21	More on-board and on-ground autonomy	4	3	3	4	3,5	5	3,5	77,3	x
22	Reduce components qualification requirements	2	5	3	2	3,5	4	5	76,8	x
23	Optimize electronics	2	4	4	3	4	4	4	76,7	x
24	Reduce number of design iterations	5	5	4	3	2,5	4	4	76,7	x
25	Heat pipes	2	3	4	3,5	3	5	3,5	76,4	x
26	Virtual thermal testing	2	3,5	3	3	3	5	4	76,1	x

Table 0.2: Top 25 ecodesign options

In a next step (step 2) a semi-quantitative analysis was done to assess the potential reduction of each option, leading to the down-selection of 10 options. In a final third step, an estimate of the required design & development effort and related environmental impact to estimate the risk of burden shifting was initiated, leading to the final selection of 6 options, namely:

1. Using alternatives to PTFE;
2. Using more efficient on-ground data management including prolonging lifetime of on-ground data processing electronics;
3. Using sustainable sources of Germanium;
4. Promoting and use system-level testing;
5. Having a better trade-off between on-board and on-ground autonomy;
6. Optimizing electronics.

In work package 3 (TN3; VITO, 2019a), the 6 selected options are elaborated and matured. Per option, a technical assessment is performed and an analysis of the environmental effects is done by LCA. The analysis is done per option, at different levels (e.g. material, satellite production and mission).

One of the environmental hotspots of PROBA-V (for the contribution to ozone depletion) is the **PTFE used in the spacecraft harnessing subsystem**. This could be tackled by replacing PTFE by polyimide or polyethylene. Both alternative materials prove to have a reduced impact for ozone depletion and human toxicity non-cancer. PI has a higher impact than PTFE in some categories like REACH chemical emissions, freshwater ecotoxicity and marine eutrophication[6]. On the level of phase CD the reduction for ozone depletion is 57%, and for human toxicity non-cancer 60%, for both PI and PE. From a technical point of view, PI has more proven qualifications than PE (e.g. space qualified, good electrical properties and radiation resilience), the use of PE would require additional qualification testing on cable level.

The **testing** creates an important environmental impact due to the electricity use and the transport of the satellite to the testing facility. The implementation of system level testing and virtual testing is further investigated and is expected to require more manhours at QinetiQ, but a reduced workload for the suppliers. Additionally, a reduction of the electricity use at subcontractors will be achieved and material requirements for test set-up will be reduced. This would reduce the environmental impact of phase CD by maximum 3%. Having the thermal tests done in a closer location[7] can reduce the environmental impact of phase CD for human toxicity cancer and non-cancer with 6% and 4% respectively. Implementing all ecodesign options for testing could lead to a reduction of up to 4% of the impact at mission level (for human toxicity, cancer). The average expected reduction on mission level is very low for all impact categories (1%).

The **level of autonomy** of the PROBA systems (space & ground segments) has been increasing with each mission. The trade-off in environmental impacts between on-board autonomy and ground operations is performed by comparing the PROBA-V to a hypothetical PROBA-V with a lower level of autonomy. The analysis shows that the actual PROBA-V has a lower impact than the hypothetical PROBA-V with little autonomy. As a conclusion, it appears that for the PROBA missions and PROBA-V in particular, the current state seems to be near-optimal in terms of workforce apportionment. It should be noted that the level of autonomy as an eco-design solution would need to be evaluated case by case. In the case of PROBA a higher autonomy has reduced the environmental impacts but this could not be the same case for other missions.

The most promising ecodesign options in terms of reduction potential proved to be the following. For these options, besides the environmental assessment of work package 3, a more elaborated environmental assessment is performed in work package 4 (TN4; VITO, 2019b). Furthermore, the cost, feasibility, risk and efforts to have them implemented and a roadmap is developed.

- Different options are suggested to reduce the environmental impact of **data processing** at VITO. Two alternatives linked to the use of servers are elaborated: use of a Mission Exploitation Platform (MEP) and reuse the servers. The MEP significantly reduces the environmental impact of the data processing for all impact categories, 33% on average with a maximum of 46% for freshwater eutrophication and human toxicity non-cancer. Extending the life time of the servers to 10 years, reduces the impact of data processing by 23% on average (with a maximum of 37%

[6] It is important to note that no recent LCI-data for PTFE are available and datasets differ significantly. A sensitivity assessment shows that for many impact categories, there is a huge difference between Ecoinvent datasets and the EF Compliant Datasets.

[7] The travel distance could be reduced from 2000 km to 300 km (return journey).

for human toxicity non-cancer). Substituting the freecooler by an adiabatic hybrid cooling unit generates an extra saving of 10% of the cooling energy, but reduces the environmental impact of data processing only with a few percent. Using LTO-8 tapes instead of LTO-6 tapes drastically reduces the number of tapes and reduces the environmental impact of data processing by 4% on average. A large reduction (24%) is achieved for critical raw materials. Combining all the options reduces the impact on mission level by 14% on average, with reductions of up to 31% for freshwater eutrophication. Critical raw materials[8] are reduced by about 28%, the effect on human toxicity, non-cancer by 26%.

The impact on cost/schedule related to implementing this eco design option is specific for each of the 6 constituting elements. Implementation of some aspects is schedule neutral, implementation of all elements is estimated to take 2.5 years. There is some cost impact associated to implementing this option.

- The **use of germanium** for the solar panels has a high impact on resource depletion. As different production routes for germanium exist, the effect of using germanium from recycled photovoltaic production scraps and as a by-product from zinc is evaluated. This has no effect on the production process of the wafers since the three germanium production routes give the same quality of germanium. Using 27% of recycled germanium and 73% from the zinc route would reduce the mission impact on resource depletion by 27%. Also for 15 other categories, the impact would be reduced slightly (up to 2%). For human toxicity, non-cancer, this would result in a minimal increase in impact (0,2%). For climate change, the impact on mission level reduces approximately 1%; however, for the power supply alone the reduction is significant (76%). The switch from germanium from the coal to zinc production route already results in an important first order reduction of the environmental impact and switching to more recycled germanium creates significant second order reduction effects.

  The production cost of Germanium associated to recycling is lower than the production through both the coal and zinc route. Technology for recycling Germanium is readily available but qualification for space use is expected to be required, taking an estimated 2 years to completion. It is expected that another 3 years would be needed to amend relevant ECSS standards and make the use of 'green' solar cells a standard practice.
- **Electronics**, and more specifically PCBs, are an important hotspot in the PROBA-V. The evolution of space electronics has been much slower than the mainstream induced by consumer electronics. At regulations level, it is clear from the consulted experts that a revision of the ECSS is recommended, not only for technical reasons but also from a programmatic point of view. ECSS is managed together by the European Space Agencies (not only ESA) and European space industry in order to reduce risks, cost and improve both quality and communication between different parties and to harmonize requirements. The aim is to continually improving the quality, functional integrity, reliability and compatibility of all elements of the project. The main challenge here is to achieve aforementioned objectives and at the same time facilitate innovation and ecodesign in a space context. The space electronics option is seen as extremely promising for the whole industry not only to improve its environmental impact but also its efficiency in general. For the technical elaboration this option has been split into several specific topics:
  - Qualify alternatives for fused tin-lead (Sn-Pb) as PCB solder finish.
  - Update solderable terminal finishes requirements.
  - Qualify/validate non-hermetic, polymer IC-packages.
  - Qualify/validate lead-free soldering.
  - Reduce the use of gold wire bonding.

[8] CRM is an indicator expressed as the weight of the critical materials that are needed in the upstream life cycle phases.

Replacing fused SnPb as PCB solder finish by SnPb HASL, Pb-free HASL, Immersion Silver, Immersion Tin, ENIG, ENEPIG and ENIPIG reduces the amount of solder but requires a solder mask. The production of this mask causes a minor increase in the impact on freshwater ecotoxicity and human toxicity non-cancer (2% and 1%, respectively). A very small decrease of the impact can be seen for metal depletion (approximately 1%). It is noted that the use of ENIG, ENEPIG and ENIPIG is currently being qualified for space applications. Replacing ceramic IC-packages by non-hermetic, plastic IC-packages creates a better thermal match and solder joint reliability, a reduction in weight and cost reduction, and a reduction of the quantity of critical raw materials by about 95%, and of ozone depletion by about 4% (on PCB level). For two impact categories, there is a slight increase of the environmental impact. It is expected that the reduction of gold will create the highest environmental impact reduction, as gold is an important contributor to the environmental impact of PCBs. For PROBA-V, not enough data are available to quantitatively assess the reduction potential of gold, which causes an underestimation of the reduction potential. On mission level, a reduction of the quantity of critical raw materials by 14% could be reached. This is due to the elimination of tungsten (used for radiation shielding) in the ceramic packages. This ecodesign option does not result in an increase of the impact in any category.
Implementing this option will lead to an overall cost reduction associated to the production of electronics. There is a need to qualify the proposed electronics manufacturing options for space and a review of ECSS standards would minimise the time and resources needed during the mission qualification. Full implementation of this eco design option, including review of ECSS standards is expected to take approximately 8 years.

A combined analysis of the environmental impacts is performed to assess the overall reduction potential of the redesign of the PROBA-V mission (figure 0.5). Including the 3 most promising options – improved data processing, more sustainably produced germanium and optimized electronics (PCBs) – in a GreenSat PROBA-V mission leads to a significant reduction in critical raw materials (42% reduction[9]), freshwater eutrophication (31% reduction), mineral resource depletion (27% reduction) and human toxicity non-cancer (25% reduction). The reduction in the other impact categories varies between 6% (human toxicity cancer and criticality weighted) and 21% (metal depletion), for no impact category the GreenSat PROBA-V mission has a higher impact than the baseline. The target of a reduction of 50% is thus not reached. The major reduction is due to the improvements in the data processing, except for mineral resource depletion for which the switch to a more sustainable germanium supply mix is responsible and critical raw materials which is because of the optimized electronics.

[9] This is a reduction of approximately 650 kg of critical raw materials, mainly chromium (373 kg) and tungsten ore (219 kg).

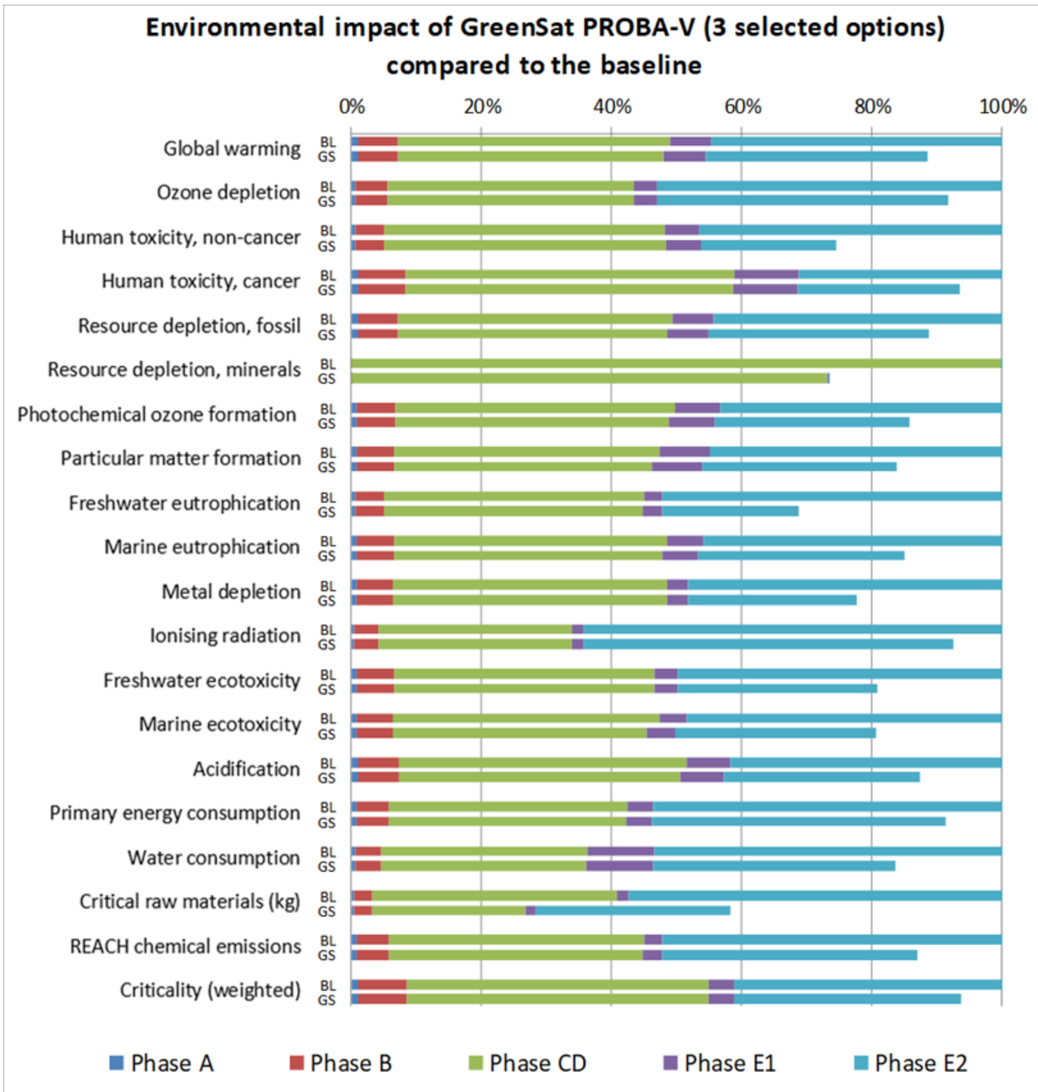

Figure 0.4: Comparative environmental profile of PROBA-V baseline (BL) and GreenSat (GS) mission (including 3 selected ecodesign options), including infrastructure

These results are based on an assessment of the environmental impact of the PROBA-V space mission including infrastructure. If infrastructure would not be taken into account, the results are quite different, i.e. the reduction potential is higher. A reduction of more than 50% is then achieved for critical raw materials and freshwater eutrophication. This is logical, since most ecodesign options focus on aspects other than infrastructure. The absolute reduction in environmental impact is similar, but the relative reduction is higher since the total impact of the mission without infrastructure is lower.

Overall, we can conclude that the implementation of ecodesign from the start of a space mission design and development process can actually reduce the environmental impact of the space mission significantly. It is recommended to focus efforts in a first instance on the environmental hotspots of a space mission as this leads to the largest improvements. Improvements are not only related to the satellite production, but as well to the operational phase of the satellite (e.g. data processing).