TRACK CORE

TOWARDS A WORLD-FRIENDLY ASSET TRACKER

Master thesis   Geert Jaspers

Author Geert Jaspers
Student Number 4667190

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Faculty of Industrial Design Engineering
Delft University of Technology
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Supervisory team Mentor: Dr. ir. Bas S.F.J. Flipsen
Department: Sustainable Design Engineering
Chair: Ir. Ruud J.H.G. van Heur
Department: Applied Ergonomics and Design

Company SODAQ
Company supervisor: Msc. Nyckle Sijtsma

Abstract

In 2022 SODAQ, manufacturer of the general purpose asset tracker: TRACK, committed itself to take environmental and social responsibility and got rebranded as a ‘World-friendly IoT’ company.
A Life Cycle Assessment (LCA) for the current TRACK product, performed by an external company, proved that decreasing the impact of the enclosure might provide a good opportunity to significantly reduce the total impact of the product.
However, two new ‘Fast Track’ LCAs showed that the plastic enclosure only contributed less than 5% to the total impact, with the electronics being responsible for the rest. Therefore the goal of the project was to reduce the impact of the electronics.

In this project an attempt was made to find a solution for the most impactful and relevant components such as the PCBA and the PV panel.
First sustainability issues of the current TRACK components were identified and then the sustainable opportunities and limitations of alternative technologies were discussed. To show at what point in time the new technologies are expected to become relevant, technology roadmaps were created.

As a conclusion of this world-friendly technology research, a vision for the future of the TRACK line was laid out in a product roadmap.
To show how the integration of the more world-friendly components could translate into practise, the TRACK Core 5G concept was designed as a showcase product. The TRACK Core 5G prototype includes a solvent-based recycled polycarbonate (PC) transparent enclosure, with electronics printed on a recycled substrate and a flexible emerging PV panel.

To extend the lifespan of the electronics, circular product design guidelines were applied. The basis of the circular loops is that the components can be disassembled quickly. In the current product the time it takes to replace the battery was relatively long (80 seconds) and the PV panel could not be replaced at all. By using the disassembly strategies and the choice for a 'direct access' design, all electronic components, including the PV panel, can be disassembled in 6-17 seconds.

In order to extend the life of the most impactful components, the chips on the printed circuit board, the theory of modular design was applied. By using the material properties of the flexible PCB, a new strategy for upgrading the PCB was developed which brings down the initial cost and offers more flexibility.

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1 INTRODUCTION

In this chapter the company SODAQ, the product that is chosen for this research, the TRACK and project goal are introduced. In addition the scope of the project, the research questions and the research method are determined.

1.1 Project introduction

SODAQs problem statement

The market for IoT devices is currently growing exponentially. While the application of IoT has the potential for companies and governments to make their processes more resource efficient and enable them to implement circular business models, the production and usage of current IoT devices also has a very negative sustainable impact. A back-on-the envelope calculation for the discarded batteries of the 100 billion connected smart devices in 2050 would fill approximately 500 Olympic-sized swimming pools, made the employees of the IoT company SODAQ realize that with the products in their current form this market can never be sustainable on the long term.

About SODAQ

SODAQ is an abbreviation of SOlar Data AcQuisition. The name is a reminder of SODAQs first product back in 2013, which purpose was to offer weather station data across Africa using a connected IoT solution powered by solar energy.
Nowadays, SODAQ has grown to a relatively small (45 employees) engineering company in the B2B market for GPS-trackers and environmental sensing devices. Their core competency is still the development of very energy-efficient IoT electronics. Since the start of the development of the TRACK product line they have set up an in-house design department experienced with producing plastic housings for long-term outdoor use worldwide. SODAQs teams mostly work on a project to project basis, meaning that the requirements of the design are largely dependent on the demands and (linear) business model choices of SODAQs clients. On the other hand, the company is responsible for both developing all hardware and software. This gives them full control over the product and provides the designers more flexibility in changing the product's architecture. Lastly, given the small size of the company (in terms of people as well as space), the amount of shipped products and the slim margins, it is not considered by the management to be realistic to set up an in-house refurbishment and remanufacturing business at the moment.

World-friendly IoT vision

In 2022 SODAQ committed itself to take environmental and social responsibility and got rebranded as a 'World-friendly IoT' company.
Efforts already undertaken by SODAQ [1] include:

1. Design solutions that support clients to become more resource efficient.
2. Implementing more energy-efficient communication protocols.
3. Communicate the intention to move away from batteries containing the conflict metal cobalt.
4. Long lasting product designs through harvesting of solar energy (TRACK Solar, TRACK Extreme) and a weatherproof design (IP67 or IP69 rating).

SODAQs raison d'être

So why is there a market need for knowing where assets are located and how does that match with a 'world-friendly' vision?

At present the logistics sector can be defined as fragmented with a lack of transparency between companies and an operation that is in general still very low-tech.
By a trend of the increasing need for more transparency and efficiency to enable more rapid and predictable deliveries and for inventory management, tracking and tracing assets is growing rapidly (Ericsson, 2020).
Additionally there is an increasing push from governments and customers of the logistics companies for more sustainable deliveries and more energy constrained zero emission transport options require more efficient planning and routing.
So the aspects that are driving the market revolve mainly on increasing efficiency and speed through transparency while reducing labour cost. How is does this match with the 'world-friendly' vision?

Lower impact operations through efficiency and monitoring

- Optimization of asset use, increasing fill rate of transports as well as reducing the amount of empty runs (which make up 15–30% of journeys in the EU (Eurostat, 2022)) through accurate dynamic planning
- Prevention and retrieval of lost or stolen assets, hereby avoiding overproduction
- Enhanced monitoring of the asset and its content to keep them in optimal condition and prolonging their life (through e.g. predictive maintenance).
- Digitization and automation of processes eliminating the use of paper

Reduced administrative burden and associated manual labour

- Avoid time lost on locating assets, potentially relieving work pressure.
- Digitization and automation of processes eliminating the repetitive and labour-intensive paperwork, freeing workers to do more creative jobs

IoT and Jevons paradox

The Jevons' paradox is a commonly cited when the terms efficiency gain and sustainability meet (Alcott, 2005). While in general it is assumed that by increasing the efficiency of a process the total impact of the produced resource will decrease as the relative impact per resource unit decreases. However due to the efficiency gain the relative cost per unit also goes down which is likely to create more demand for the resource. As a demand curve is almost never linear this might lead to the extreme case that demand will rise significantly, hereby fully eliminating any efficiency gains and will even lead a larger total impact, hence the paradox.
As SODAQ is serving a number of clients in the air freight sector, a sector known for its high environmental impact, it is debatable whether this would in line with their 'world-friendly' vision. When applying the theory of Jevons' paradox it is possible that the efficiency gains by SODAQs trackers will cause more air traffic and emissions.
However, there is a way to counter the 'rebound effect' by introducing quotas or price compensation in legislation. A good example is the upcoming introduction of CO_2 pricing in the European Emission Trading System for the maritime and aviation sectors in 2024 (European Commission, 2022). In this case the efficiency gains help to meet the demand with the same or lower impact.

1.2 Product introduction

All-purpose asset tracking device

The TRACK is the flagship device of SODAQ and it is marketed as go-to all-purpose asset tracker to cover its clients' general high value assets tracking needs. To cover a broad range of use cases SODAQs intention was to create "the most versatile asset tracker on the market" so not all TRACKs are created equal.

Enclosure variants

The SODAQs sales team can configure the TRACK according to the requirements of the client. There is a choice between three different connectivity options, an option for a PV panel or a button, alkaline or rechargeable batteries and a wide range of integrated sensors.

The product line comes in three flavours: the Solar, the Active and the BLE. A fourth variant exists with LoRa connectivity, however this variant is not actively marketed. At the moment the Solar is the bestseller of the line as it provides the longest estimated battery life of 7 years or more and can send more messages per day than the Active.
The variants, shown in figure 1 are constructed using the following enclosure elements:

- two top housing designs: one with room for PV panel and one with a 2K injection-moulded button on top
- two bottom housing designs for two mounting options: one with and one without flanges.
- The BLE variant comes with watch sized beacons with a type of puck shaped enclosure.

Figure 1: Enclosure variants (a)Solar with flanges (b) Active without flanges (c) Beacons

Bracket

For assets that for which the current mounting options is not suited, SODAQ could design an asset specific bracket (see figure 2).

Figure 2: Custom made TRACK Bracket design

1.3 TRACK use cases

In the marketing material of the TRACK several potential use cases are specified:

- Logistics – containers, delivery trucks
- Port Terminal – containers, on-site vehicles
- Construction – vehicles, materials, machinery, waste containers
- Airports – trailers, tow bars, equipment, luggage carts

Since its introduction in 2021 the TRACK is already used in the following cases (among other):

Seed containers

These container are used to transport highly valuable seeds to farmers. This is a closed loop logistics operation meaning that the asset should be kept in the loop for reuse in succeeding deliveries. The main purpose of the product is to prevent the container to be lost and a new one to be produced. Currently up to 1 out of 6 containers disappear every year.
A second feature makes use of the sensors in the TRACK. The sensors are able to register when the farmer has unlocked the container (see figure). Once the alert has been received by the seed company, a bill is sent to the farmer automatically.

Flight cases

Flight cases are being sent around the world by airplane. Tracking the whereabouts of the flight cases can not only inform the end customer whether the content arrives just-in-time but also alert the transport company whether an asset gets lost or stolen and where to retrieve it.

Luggage carts

In this case the location of the luggage carts is registered using the TRACK. This way the equipment can be used at the right place at the right time with less fuel consumption of the truck. Furthermore maintenance of the carts can be scheduled based on the usage, improving the uptime and prolonging their functional life.

1.4 Project scope

World-friendly IoT vision expansion

SODAQs focus for the future is a step-by-step expansion of the vision to not only decrease the indirect impacts from its clients and their assets, but also to decrease the direct impact of SODAQs product portfolio in terms of CO_2 emissions during the total life cycle of the products. This expansion will be translated into design for circularity (taking back used products into the manufacturing process and reusing electronics in new/refurbished products), planned permanence (devices designed to last longer), and responsibly sourced materials (SODAQ, 2022).

Project scope

This graduation assignment is a first step on the road to realising the expanded vision and is framed as improving the sustainability of the physical enclosure of the TRACK product line (see figure 3), with a focus on responsibly sourced materials (plastics). An LCA for the current TRACK has been performed by an external company. The outcomes proved that decreasing the impact of the enclosure might provide a good opportunity to significantly reduce the total impact of the product. According to the study the plastic housing of the TRACK Active (with alkaline AA batteries) contributed 70% of the total CO_2 footprint of the product.

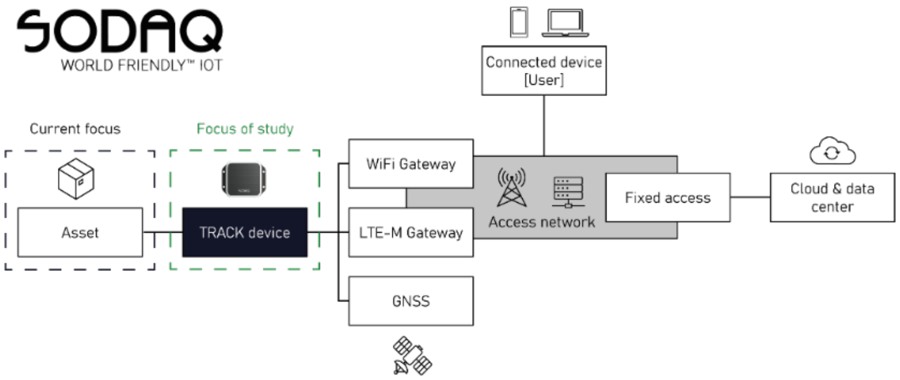


Figure 3: current and expansion of the focus for the 'world-friendly' vision

TRACK Solar circular redesign case study

Furthermore the data from the LCA study showed that the Solar variant has a significantly larger carbon footprint, due to its solar panel. Together with the fact that the Solar is the bestseller of the TRACK range, the choice was made to focus the analysis and the sustainability improvements initially on this variant.

Impact definition

Traditionally, in a linear economy, sustainability is typically measured in impact per produced product (cradle-to-gate). Strictly a cost analysis. While a more sustainable product in a circular economy often is defined by a cost-benefit analysis. In that case a more durable material might still turn out to be beneficial option even though it is produced using a more energy-intensive process. Comparing the impact of design alternatives for a tracking product are therefore about looking at relative CO_2 impact per location message.

By designing opportunities that keep the product functional for longer and making it simple to be reused over multiple lifecycles, the CO_2 impact per message will go down.

1.5 Design approach

The new 'World friendly' Track product line should be designed for a circular business model such that the CO_2 impact will be lowered compared to the current generation. For the redesign the focus should be on the mechanical parts of the product. The main question that project tries to answer is: How can the SODAQ TRACK line be redesigned to fit in a circular business model?

Research questions

To understand what components and materials should be the focus of redesign an impact assessment is done.

1. **What is the current impact of the product and its components?**

1.1. Which components and which life stages have the highest potential for impact reduction through a redesign?

1.2. What is the highest potential impact reduction for the housing components specifically?

To provide an insight into what parts of the product are adhering to circular principles already and what parts are not, the track is scored on the relevant criteria.

2. **What are the relevant scoring criteria to assess the TRACK on the principles of circular design and determine how circular the TRACK in its current form already is?**

Next, the most relevant circular strategies are chosen based on the highest potential

3. **What circular strategies have the highest potential for reducing CO2 impact?**

3.1. Which components, failure modes or company strategies are likely to limit the maximum lifetime of the product?

3.2. How to assess the component state and decide on their eligibility for reuse cycles?

3.3. What circular business model would enable SODAQ to bring circular products to the market the most quickly?

Finally, the product is redesigned according to the chosen principles.

4. **How should the product design be adapted to meet the identified circular strategies?**

4.1. How can the redesign be validated to match the scoring criteria identified in RQ2

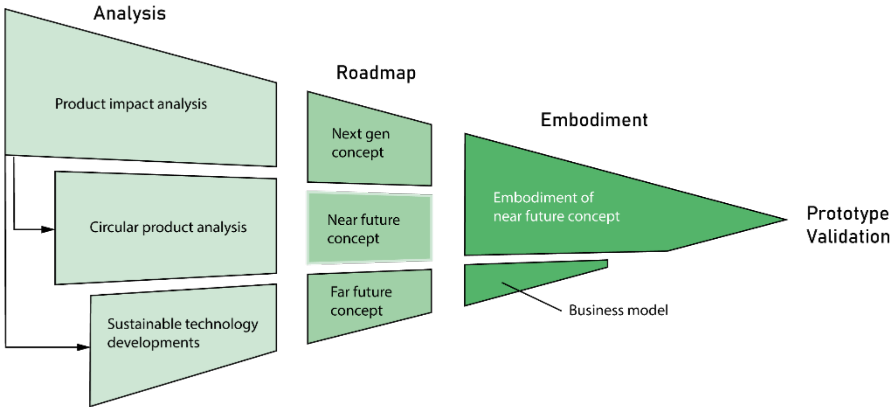
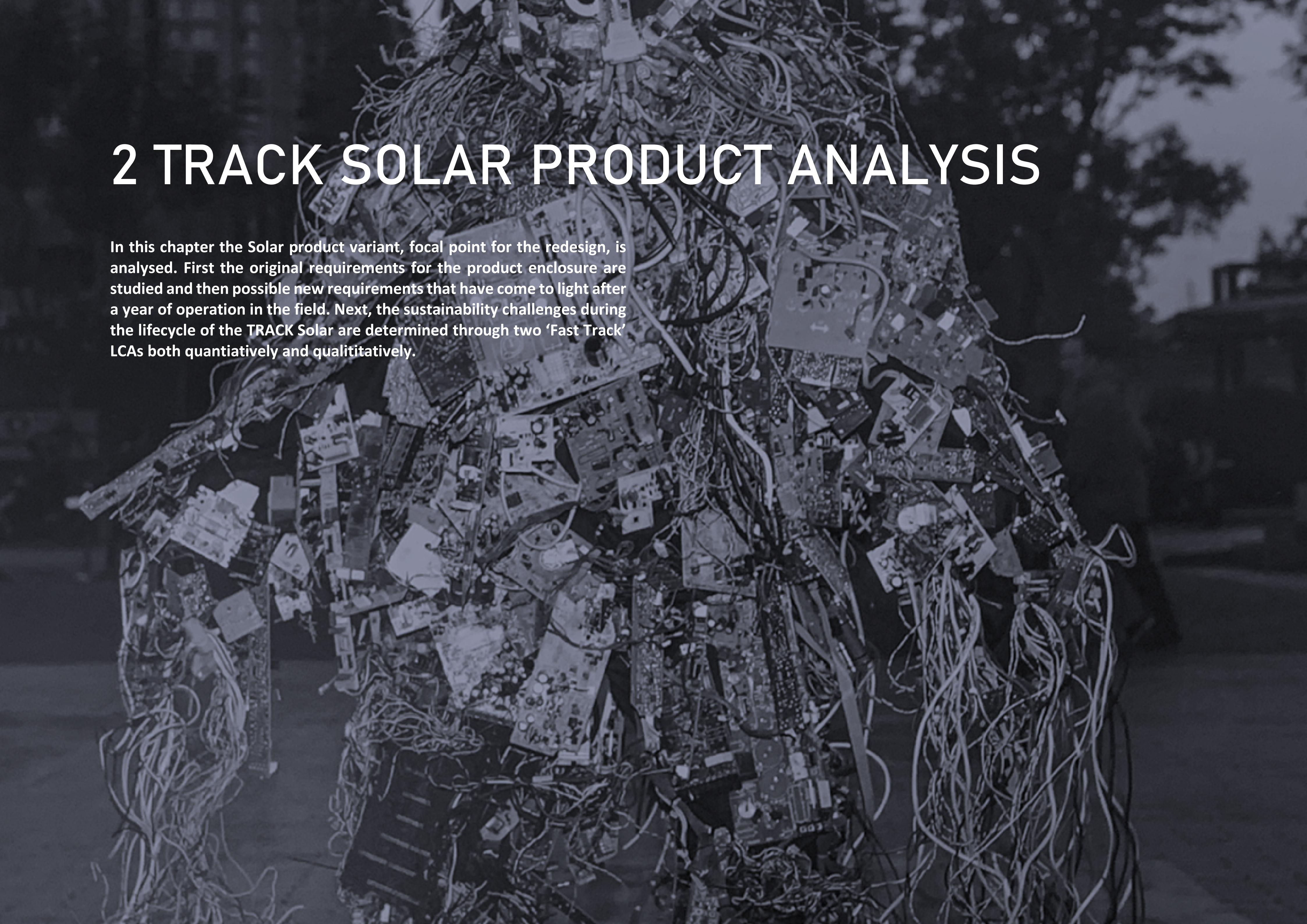


Figure 4: Outline of the project

2 TRACK SOLAR PRODUCT ANALYSIS

In this chapter the Solar product variant, focal point for the redesign, is analysed. First the original requirements for the product enclosure are studied and then possible new requirements that have come to light after a year of operation in the field. Next, the sustainability challenges during the lifecycle of the TRACK Solar are determined through two 'Fast Track' LCAs both quantiatively and qualititatively.



2.1 TRACK Solar requirements

To understanding of the product (figure 5) and to answer the question how and why the product got its current shape and feature set, an investigation into the different aspects related to the product enclosure was performed. This was done by interviewing the designers of the PCB, the antennas and the housing and going through every piece of documentation that was available about the product.

An existing program of requirements from the early development stages of the TRACK was taken as basis for the analysis. After gaining more insight into the existing product requirements, it became clear that not all requirements were mentioned on the list. The new requirements list can be found in appendix A1.

Antenna performance
The most important requirements for the enclosure result from ensuring optimal antenna performance. For instance the material options: constructing the enclosure out of conductive material can better be avoided. Moreover, the antenna clearance defines the complete build-up of the product: from the dimensions of the PCB (see Appendix A3) and the PV panel to the position of the battery. For example although optically the PV panel covers the entire top surface in practise this is not case as the copper traces above the antennas would create signal interference. The beam direction and the associated clearance for the three antennas are visualized in section 2.2.

Weatherproof design
Furthermore there are requirements applicable to durable outdoor products such as a weatherproof, IP67 rated construction.

PCB components
Then there are specific requirements for some PCB components.
The requirements (for all currently configurable components) are registered in a separate list of appendix A2.
Being on the market for over a year it has become clear that not all sensors of the TRACK are used by SODAQs clients. Consequently only the most important sensor requirements are included into the main program of requirements.

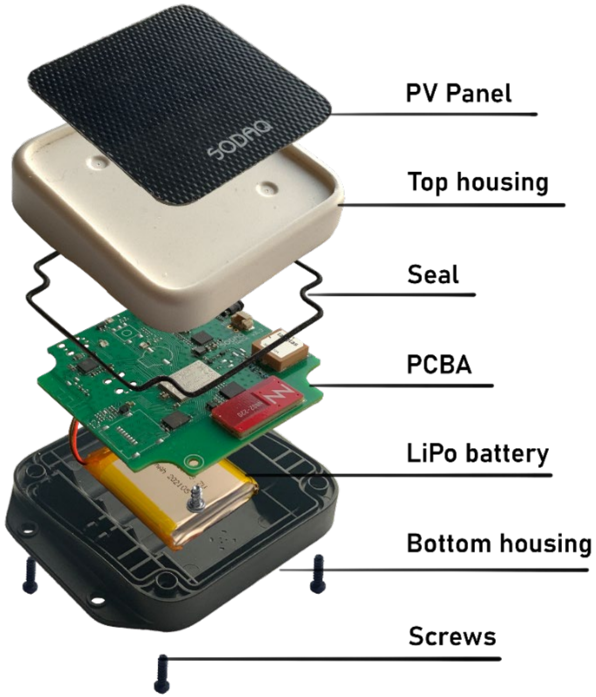
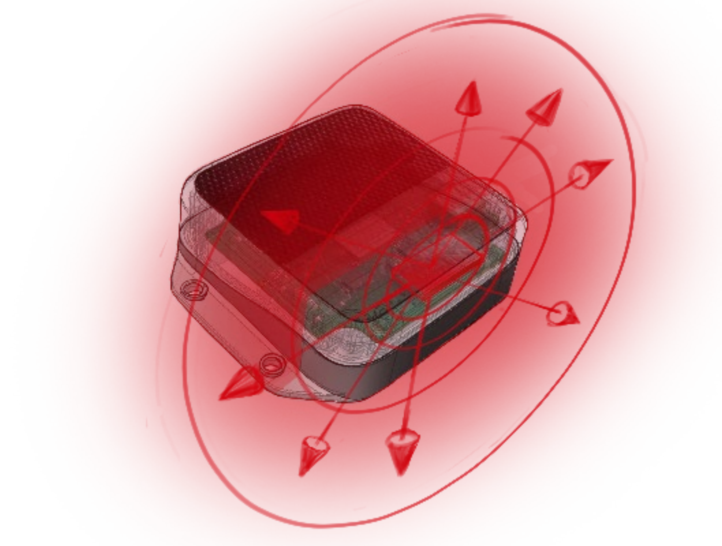


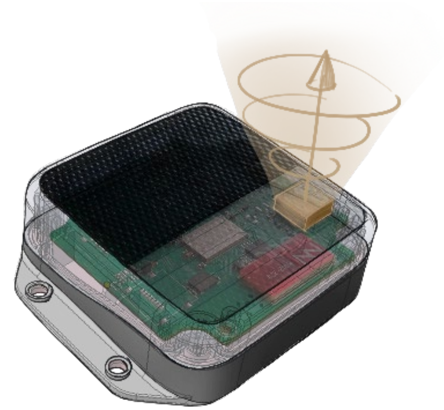
Figure 5: TRACK Solar component overview

Antenna requirements

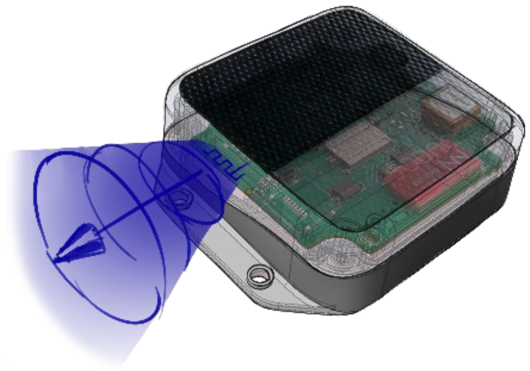
LTE-M



GPS



WiFi



	LTE-M	GPS	WiFi
Position Accuracy	**LOW** [50-100 m] Available in areas with LTE-M coverage. Improved accuracy through triangulation.	**HIGH** [5-20 m] Available worldwide. Unreliable inside buildings and within dense urban areas as accuracy is influenced by surrounding metallic structures	**MEDIUM** [10-50 m] Successful positioning ‘WiFi sniffing’ depends on the coverage of WiFi access point. Improved accuracy through Triangulation. Unreliable in rural areas.
Energy usage	**LOW** Location calculations are performed at the back-end side	**HIGH** Energy intensive location calculations are performed on the device	**LOW** Location calculations are performed at the back-end side
Data	Used for data communication		

2.2 ‘Fast Track’ LCA

Given the low informative and even erroneous nature of the currently available LCAs it was considered necessary to get a better grounded insight into how the impact of the housing compares to the electronic components. Given the short timeframe of the project conducting a ‘Fast Track’ LCA seemed to be the best option. It is important to acknowledge that a ‘Fast Track’ LCA is not a replacement for a full LCA, but the outcome should provide a good indication of the impact of the main components and lifecycle stages quickly. A full LCA in commercial LCA software like SimaPro or GaBi can take up to 2-3 months to complete.
So before starting, the focus for the Fast track LCA needs to be determined.

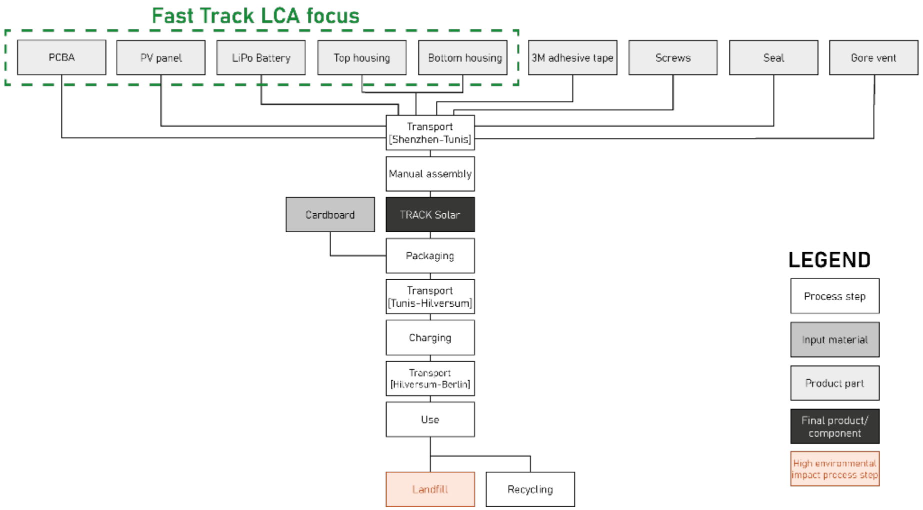


Figure 6: Product life cycle stages and LCA focus

System boundaries

The system boundaries can be determined after mapping out the different life cycle stages of the product (as presented in figure 6). The focus should be on the life cycle stages and the components, which are responsible for the bulk of the impact.
Based on the Bill of Materials (BoM) for the TRACK Solar (shown in appendix B2) first a selection was made of the components to include. The 5 components that make up around 95% the total weight were selected for further analysis (see figure 6).
To determine the relevant life cycle stages LCAs of comparable products, such as an outdoor temperature and humidity sensor (Yung, 2011) and smartphones (greenproductdesign, 2022) were studied. These LCAs show that for electronic products with relatively complex ICs the main impact would lie in the material sourcing and production phases. This was confirmed later by Granta’s CES EduPack EcoAudit tool figure 7).

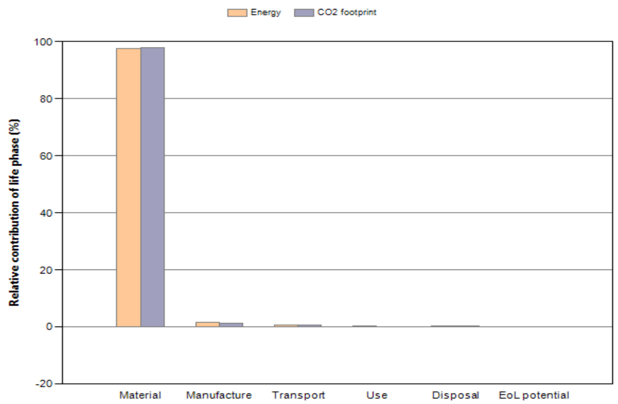


Figure 7: Relative Impact of the life cycle stages for TRACK Solar

Impact metric

A full LCA can cover many sustainability aspects. Variables such as Green House Gas (GHG) emissions, Cumulative Energy Demand, 'ecocosts', water use, human toxicity, ecotoxicity to name a few can be outputs. In general it is safe to say that GHG emissions/Global Warming Potential (GWP) with the unit kg CO_2equivalent is the most commonly used metric in LCA literature. This makes sense as most sustainability goals of companies and governmental policies are related to reducing the CO_2 impact, for example Scope 1 (CO_2) emissions or net-zero (CO_2 emission) targets found in company corporate sustainability reports.
Therefore the decision has been made to take kg CO_2e as the impact metric for Fast Track LCA.

Fast Track LCA tools & results

With the focus for the Fast-Track LCA defined and with some high level knowledge about the materials and main production processes, an outcome could be generated relatively quickly. This made it possible perform a second analysis, using a different database. The first LCA was made using the Idemat 2022 database and an Excel file for data processing. The second LCA was made in the CES EcoAudit tool and uses the CES materials library as input data.
It was expected that the second LCA would support the first one to get a more definitive answer. Unfortunately the results, which are depicted in figure 8, clearly reveal the limitation of the Fast Track method when applied to electronic components as the outcomes differ significantly.

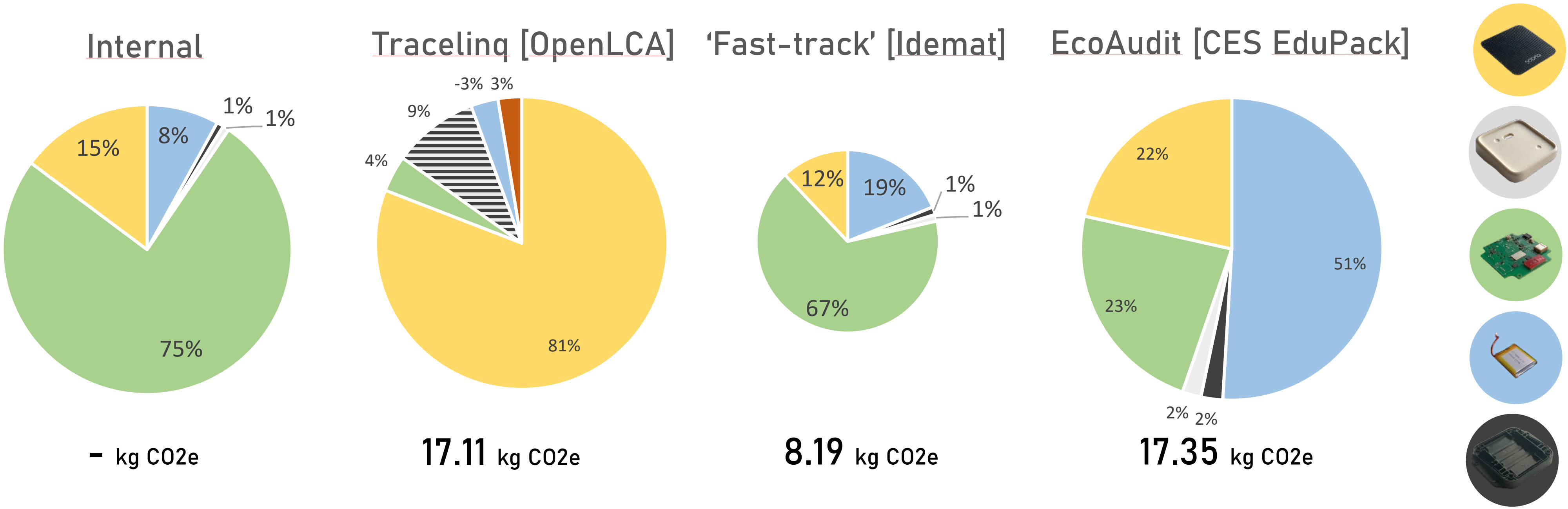


Figure 8: Relative impact of the main components

Fast Track LCA discussion

With such significant differences in the outcomes for both the relative impact distribution and the total impact, it becomes hard to form a conclusive answer on which components have the highest contribution.
When contacting TU Delft staff, experienced with conducting LCAs, about the question which one of the two LCA outcomes could be closest to reality it turned out that they also did not know which database to trust more. Electronic components are just too complex to provide useful estimates for. The only way to know for sure is by diving deeper into the subject and conduct a full LCA. An alternative could be to make an educated guess based on LCA literature of small electronic products with relatively similar types of components, such as IoT products and smartphones.

LCA conclusion

The impact of the enclosure is significantly lower than expected

The electronics make up the vast majority of impact of the product, while the impact of housing material is likely below 5% of total impact of the TRACK Solar. Even for the TRACK Active the contribution of the enclosure will likely be very low, considering Fairphone's LCA. This means that only looking at changing the enclosure material would not be enough to make a meaningful step towards the world-friendly future and it might even be close to an act of greenwashing. This means that the project scope should be augmented.

The Fast Track LCA method has its limitations

Theoretically a Fast track LCA has great potential to get a good overview of a product's impact in short timeframe. However in practise the method is only useful to some extent. If a designer wants to design a products with a limited amount of materials, mixtures consisting of a few materials, using materials that are commonly applied and using production processes that have only a few steps the outcome is likely very informative. Unfortunately few electronic component can be placed within these bounds of limited complexity.
Therefore the current conclusion should not be considered as a definitive answer. Rather it would act as a recommendation to take the step towards conducting a full LCA.

2.3 Detailed LCA

With the problem statement it becomes possible to focus design efforts in lowering the impact of the electronics in the redesign. Unfortunately the data itself does not provide much insight into the specific causes for the high impact. Furthermore because of the focus on one specific metric, other well known sustainability issues might have been missed. Finally, better knowledge of the sustainability issues will be useful later in the process when particular sustainability claims of competing technologies unrelated to lowering the CO_2 footprint need to be judged.
Therefore qualitative research is necessary which provides context to the 'Fast Track' LCA without the long struggle of conducting a full LCA.

Method

The focus of the qualitative LCA will again be on the sourcing and production stages of the main components. However additional attention will be paid to recycling issues. This is relevant as recycling is considered an important aspect of a more circular economy (See chapter 2.7).

1. The components in the TRACK are mapped out, from the refinement of the raw material up to assembly. To understand the potential causes for impact during production stages a the typical production process for the components in the TRACK are mapped out, from the refinement of the raw material up to assembly.
2. The most impactful steps are highlighted in red, either based on if it requires a high temperature (i.e. energy intensive), whether hazardous chemicals are used, or if any other specific sustainability concern is raised in literature.
3. Mapping these processes out also shows what the input materials are that need to be sourced for the production of the component. This then helps to find potential causes for sustainability issues for these raw materials.
4. Finally the main recycling pathway (if any) is described together with its corresponding issues.

Literature review results

Here the results from a literature review on the various lifecycle stages of the components included in the 'Fast Track' LCA are presented on the next page

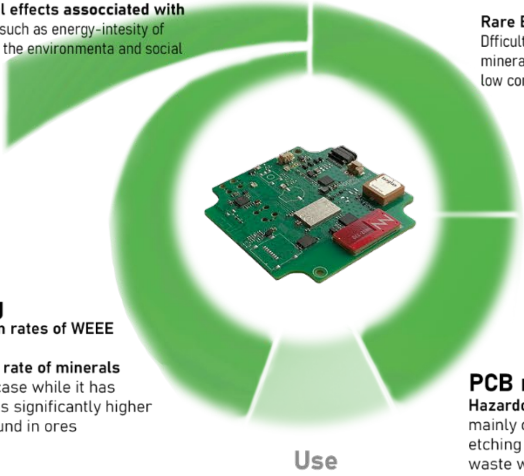
PCBA

Mining
Large number of periodic elements due material complexity of electronic components make chain of custody almost impossible

Negative external effects asscociated with mining activities such as energy-intesity of digging, impacts on the environmenta and social issues

Refining
Electronic grade silicon for silicon wafers, the basis of a chip, silicon needs to have a purity of 99.99999999% and is therefore an impactful process

Rare Earth Elements (REE)
Dfficult due the similarity with other minerals in their atomic structure and the low concentrations in the ores



IC manufacturing
Productiion of ICs is known to have a high impact but there is a knowledge gap regarding the exact numbers and cuases due to the complexity of the production steps (1000+)

PCB manufactuing
Hazardous production waste
mainly cosists of the copper etching solution and copper rich waste watterand

Recycling
Low collection rates of WEEE

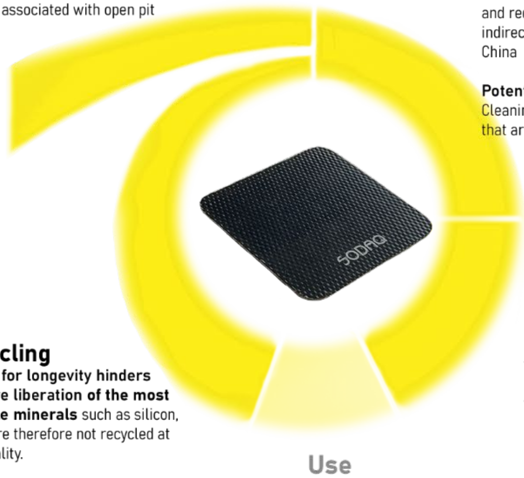
Low recovery rate of minerals
<20% in best case while it has concentrations significantly higher than those found in ores

PV panel

Mining
High purity quartzite mining has typcical negative external effects associated with open pit mining

Refining
PV grade silicon needs to have a purity of 99.999999%, is extremely energy intensive and requires coal cokes directly and indirectly, through coal-fired power plants in China

Potent green house chemicals
Cleaning of reactors is done using chemicals that are 22,000 times more potent than CO2



Manufacturing
Energy and chemically intensive cell production
for deposition of the electron emitter layer and texturizing of the slicon wafer to improve efficiency of the cell

Recycling
Design for longevity hinders effective liberation of the most valuable minerals such as silicon, which are therefore not recycled at high quality.

LiPo battery

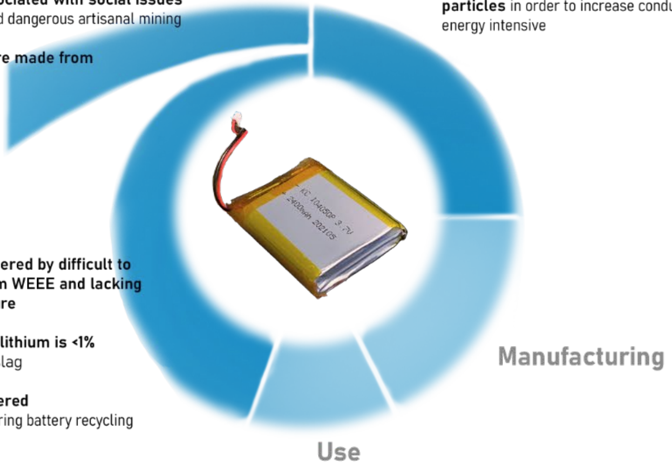
Mining
Lithium mining from bine leads to water stress, while hardrock mining puts pressure on the local enviroment and has a high CO2 impact

Cobalt mining is associated with social issues
such as child labour and dangerous artisanal mining

Synthetic graphite are made from fossil-based cokes

Refining
Lthium cobalt oxide (battery cathode) production requires an energy intensive calcination process

Carbonization of the coating of the graphite particles in order to increase conductivity is energy intensive



Recycling
Recycling rate is hindered by difficult to remove batteries from WEEE and lacking recycling infrastructure

Low recovery rate of lithium is <1%
as it gets lost in the slag

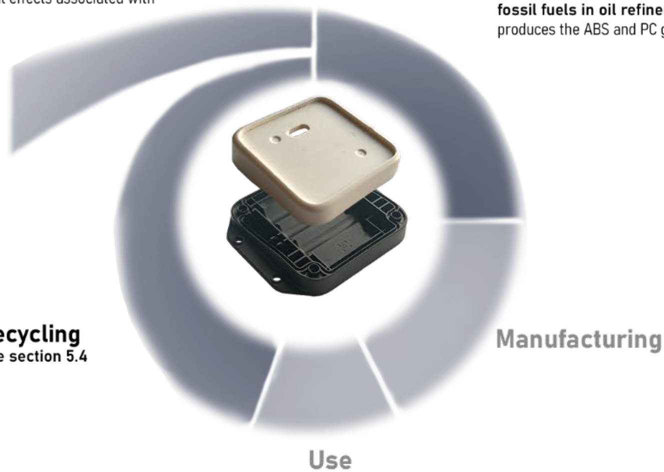
Graphite is not recovered
as it gets incinerated during battery recycling

Enclosure

Drilling
Virgin plastics are derived fossil-based sources.

Drilling of oil has typcical negative external effects associated with mining

Refining
intensive refinement process of fossil fuels in oil refineries to produces the ABS and PC granulates



Recycling
See section 5.4

LCA conclusion

The goal of the LCA was to get a closer insight in the sustainability issues and challenges during the lifecycle stages of the main TRACK components, specifically the sourcing, production and recycling stages. From this assessment it has become clear that the sourcing stages are generally much more impactful than the production stages, except for IC production perhaps due to its enormous complexity.

The mining of the wide range of minerals required for the electronic components is the cause of a wide range of environmental issues. Additionally, the refinement steps of certain mineral can get extremely energy and chemically intensive. Electrically powered or heated using relatively cheap fossil based sources that will be hard to replace anytime soon.

All in all, looking from a sustainability point of view one would think there is such a strong case to be made for using more recycled materials. And especially for materials recycled through processes that avoid the use of such energy intensive refinement processes.

Unfortunately the research into the recycling pathways has shown that both due to unfair competition from primary sources and due to the trouble of getting the specific components out of the WEEE in sufficient volume, the recovery of valuable minerals is often lacking as it is not considered economically viable.

This mainly comes down to extremely durable (inseparable) or materially complex (using a wide variety of materials, mixed in low volumes) component design, which means a lot of effort is required to get to the material out in the first place and secondly to get the volumes necessary for companies to start investing in recycling technology to deal with this poor component design.

Even if better designs are adopted today, recycling won't be profiting from them for many years come. Until the EU or member states require it through regulation, it is unlikely that components with lower impact recycled materials are coming to the market anytime soon. So the question then becomes what to look for in more sustainable component alternatives are there in case no recycled fractions can be used in current component designs?

The following guidelines need to be taken into account when alternative components and technologies are researched in terms of their sustainability performance (Bakker, 2019):

More sustainable material sourcing

- Components that require less input materials
- Components that use materials from a traceable or certified source
- Components that are made with materials that require less energy and chemicals for mining and refinement
- Components that are made with materials that do not require primary materials from a fossil origin or require fossil sources for refinement

More sustainable production

- Components that are produced with less energy and chemically intensive process steps

Designed for recycling

- Component designs that focus on the liberation of the materials or have a less complex material composition
- Manufacturers that are open to sharing material composition information with recycling facilities

2.4 Product failure modes

The TRACK line has been introduced only recently and products have been in the hands of customers for a year. This means SODAQ cannot yet provide any long term failure reports. However, SODAQ does receive feedback about early part failure; combined with estimates about component lifetime, the following potential failure modes are identified:

Weather

- Currently the main failure mode is related to inconsistent water ingress protection. Before recent adjustments, rain could enter via the PV panel opening and the USB-C port (figure 9a).
- The PV panel lifetime is specified for at least 8 years. Beyond this point delamination of the top layer might occur.

Vibrations & impact

- The GPS module solder connection can break due to excessive vibrations and impact from falling.
- The flanges have a chance to break during an accidental drop or during dismounting (figure 9b).
- The accelerometer has moving mechanical parts that can wear/degrade over time, hereby lowering the sensors' sensitivity. In case the sensitivity becomes too low TRACKs wake up signal might not be triggered, keeping the device in an endless sleep. No estimate or data is available about the lifetime of the sensor.
- The friction fit JST connectors for the battery and PV panel can shake loose over time.

General component degradation

- A LiPo battery has limited amount of charge cycles as the charging capacity decreases due to aging effects. Therefore the battery is likely the first component to limit the functional life of the TRACK.
- Flash memory can degrade over time through continuous read/write actions. It is not known if this will become problematic during the lifetime of the TRACK.

Obsolescence

- After the products first life ends after an estimated 7 years the current network technology might no longer be supported by operations in parts of the world. For example 3G bands have been discontinued already and 2G will be discontinued in 2024 in the Netherlands.
- Because the SIM chip is soldered to the PCB, swapping network operator would require a new chip and thus reworking the PCB. In the scenario where the operator discontinues its service, the product will become unusable.
- End of support for electrical components limits the repair and refurbishment options for the PCB.

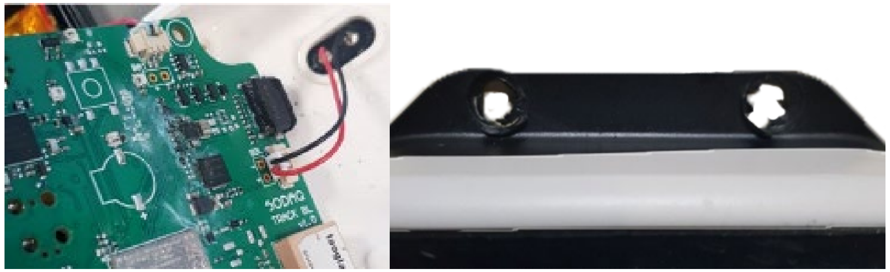


Figure 9: (a) PCB failure after a water ingress protection test (b) damaged mounting holes after dismounting from asset

2.5 Product analysis conclusions

- Antenna performance dominates the design in terms of product dimensions, materials and product packaging architecture.
- The IP rating will be the second most important design requirement as water intrusion will be the most likely short term failure mode.
- Long term failure modes such as battery degradation, mobile network end-of-support and reusable flange design need to become focus points for lifetime extension.
- Performing a 'Fast Track' LCA can provide insight into the impact of components very quickly, but the usefulness for electronic products is very limited as their material composition is too complex.
- The results of both LCAs are combined into figure X. It shows the mean of the calculated percentages and rounded off with a resolution of 5%.
- The 'Fast Track' LCAs show that the sourcing and production stages of the electronic components cause the nearly all of the impact of the product, while the relative impact of the enclosure is almost negligible (figure 10). This means that reducing the impact of the enclosure should no longer be the main aim of the project, instead the focus should be on reducing the impact of the electronics.
- According to similar LCAs the highest impact of the TRACK will most probably be attributed to the sourcing and production stages of the 15 ICs. This seems to be supported by the qualitative LCA, although the cause for the impact remains unclear due an identified knowledge gap.
- More specifically: the highest impact of the other electronic components lies most likely in the energy and chemical intensive sourcing (mining and refining) of the minerals. The mining step might also have tragic social implications on top of that, as is very well documented for case of cobalt mining in the DRC and biodiversity loss.
- Recycling of the electronic components will probably the best way to avoid most sustainability issues. Yet in practise recycling is, apart from plastic, either virtually non-existent or the recovery efficiency of valuable materials is very low due to numerous challenges that mainly come down to poor product and component design and a general lack of information about material composition of components.

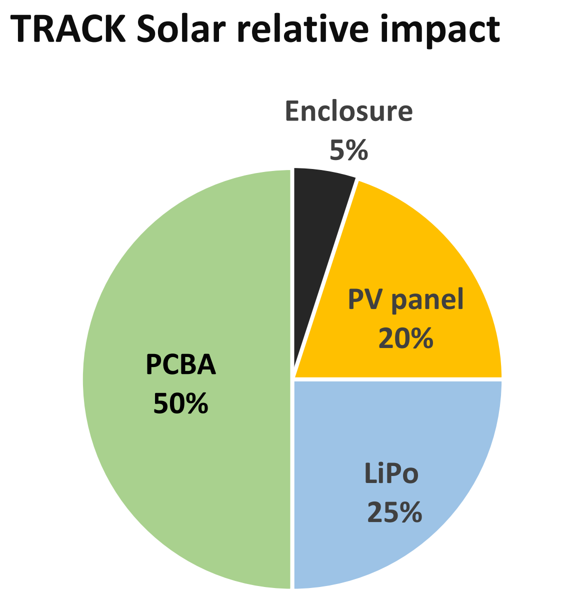


Figure 10 : Mean impact from Fast Track LCA

2.6 Revised problem statement

Reducing the impact per message through lowering the impact of the enclosure should no longer be the single goal of the project. **A truly 'world friendly' product can only be achieved if the focus shifts towards lowering the impact of the electronics.** This further underlines the need for circular product design to keep the electronics in optimal condition.

3 CIRCULAR PRODUCT ANALYSIS

Design for a circular economy starts from the premise that the flow of products and materials must change; the flow of products, components and materials must be slowed down and they must be kept flowing, in circles. A system without dead ends or open ends; a circular system.
This requires care. Not only from users and from manufacturers, but especially from the designers that can intentionally put the love of caring into these products, components and materials themselves and in the system that support them.

This chapter is meant as an introduction to the subject of circular product design. It starts with an overview of the different loops from the technological cycle of the butterfly diagram (Ellen MacArthur Foundation, 2019) and then assesses directions for improvement through the use of a disassembly map and a circularity assessment.
Although ultimately future TRACK products should be ready for as many loops as possible, the goal of this chapter is to narrow the scope and make a decision on which loops to focus for the initial 'world-friendly' redesign. To this end the relevance of more circular business models for a tracking product is researched and the business models and loops discussed with SODAQ.

3.1 Circular loops

Product integrity and the inertia principle

Product integrity is defined as the extent to which a product remains identical to its original (e.g., as manufactured) state over time (den Hollander, 2018). The higher the product integrity the higher the added economic value. This concept is visualized in the value hill in figure 11.
In the circular economy the concept of product integrity is linked to the inertia principle: keeping the product integrity as close to the highest level for as long as possible, while minimizing the environmental and economic costs for preserving or restoring the product's added economic value.
This means that the interventions that can bring the product back to highest level of product integrity with the lowest cost are preferred.

Strategies for preserving product integrity

he product can be brought back to a high level of integrity through the following strategies/loops in order of preference (Bakker, 2019):

(Predictive) maintenance
The performance of inspection and/or servicing tasks at regular intervals, to retain a product's functional capabilities and/or cosmetic condition

Repair
Bringing a non-functional product back to working condition

Reuse
Reusing a product for the original or a new purpose without further reprocessing, excluding cleaning

Refurbishment
Returning an used product to satisfactory working or cosmetic condition by replacing important parts that are damaged or predicted to break down in the near future

Upgrading
The process of enhancing, relative to the original design specifications, a product's functional capabilities and/or cosmetic condition

Remanufacturing
Returning a used product to at least its original quality, with a warranty equivalent to, or better than the original product

Recycling
Recovery operation where a waste material is processed to create new products and materials intended to serve its original or a new purpose

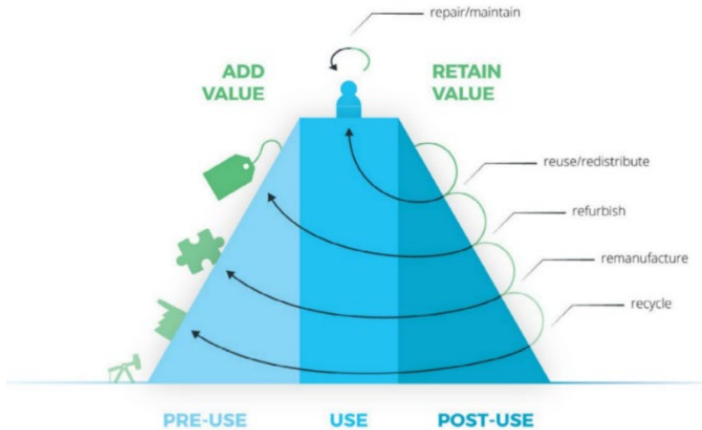


Figure 11: Value hill of a circular product (Achterberg, 2016

3.2 Disassembly map

Design for disassembly is essential for all circular loops (except for reuse). The disassembly map is a visual method to map the architecture of a product and highlights the focus points for a (re)design focused on improving disassembly (De Fazio, 2021). The disassembly process of the TRACK Solar is translated to figure 13 and has the following features.

Action blocks

The decision for the type of connection between two parts defines both the type of tool and the loosening force necessary. Information about these three aspects of the connection is represented in a single action block, using different visual cues such as shapes, colours and labels. For example connections that require a high loosening force are highlighted by a red colour which indicate that those actions leave room for improvement.

Disassembly penalties

Next to action blocks, there are specific disassembly penalties:

- The action needs to be performed with care as it can cause irreversible damage otherwise (e.g. the soldered connection of the PV panel can break relatively easily).
- The connection does not allow for reuse after the disassembly step (e.g. damaged mounting holes after dismounting from asset)

Hot spot indicators

Finally, the targets for the disassembly process are highlighted by hot spot indicators. Such target components can be:

- Priority components, which are the parts that have the highest chance of failure and need to accessed quickly.
  These include the PCBA in case electrical components on the board have failed, the battery if it no longer has sufficient capacity left and the PV panel damaged from external impact.
- Components with a high economic value are parts that either can be harvested and reused cost-effectively.
  The PCBA is the most costly part, so harvesting of the PCBA might make sense from an economic point of view.
- Components with a high environmental impact, which in case of the TRACK are all electronic components (see chapter 2).

Disassembly time

The disassembly time and depth was determined using a video recording of the disassembly process using an electric drill.

TARGET COMPONENT	STEPS [#]	TIME TO ACCESS [MIN]
PCBA	6	1:00
LIPO BATTERY	7	1:20
PV PANEL / TOP ENCLOSURE	8	> 5:00
SEAL / BOTTOM ENCLOSURE	9	1:30

Redesign focus points

1. **Battery disassembly sequence**
   The relatively high time to access the battery, the main priority component, can be explained by looking at the disassembly map in figure 13. The number of steps (disassembly depth) it takes to get

to the battery is relatively high, as the PCBA needs to be unscrewed first (see figure 12a).

2. **Adhesive tape alternatives**
But the problematic steps during the disassembly are the liberation of the battery and especially the PV panel. Both parts are attached to the enclosure with a strong non-reusable 3M adhesive tape (figure 12b), which can only be removed with high force intensity. And to make removal extra tricky, the PV panel lies recessed in the enclosure. This makes it almost impossible to disassemble the component with common tools either quickly or without damage. The tape also disintegrates and leaves residues on the parts, which might hamper recycling.

3. **Secure cables connections**
The cable of the PV panel broke off at the solder pads when disconnecting the force-fit battery connector from the PCB (with the PV panel still connected to the PCB, simulating a battery swap).

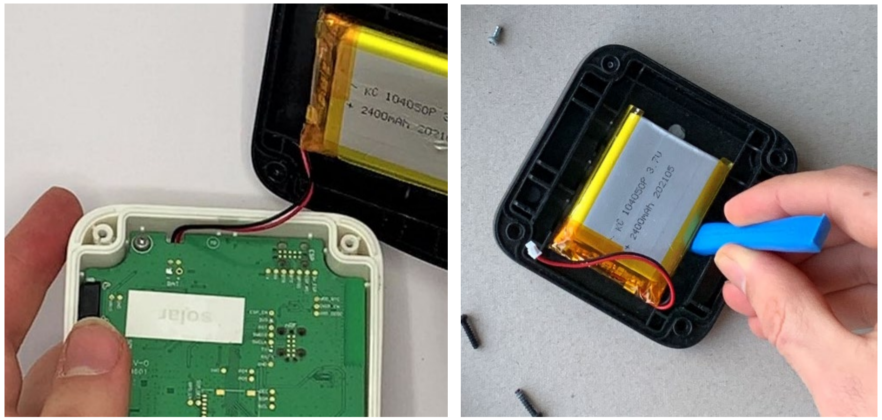


Figure 12: (a) Inaccessible battery connector (b) Overcoming the battery adhesive force by using a spudger as lever

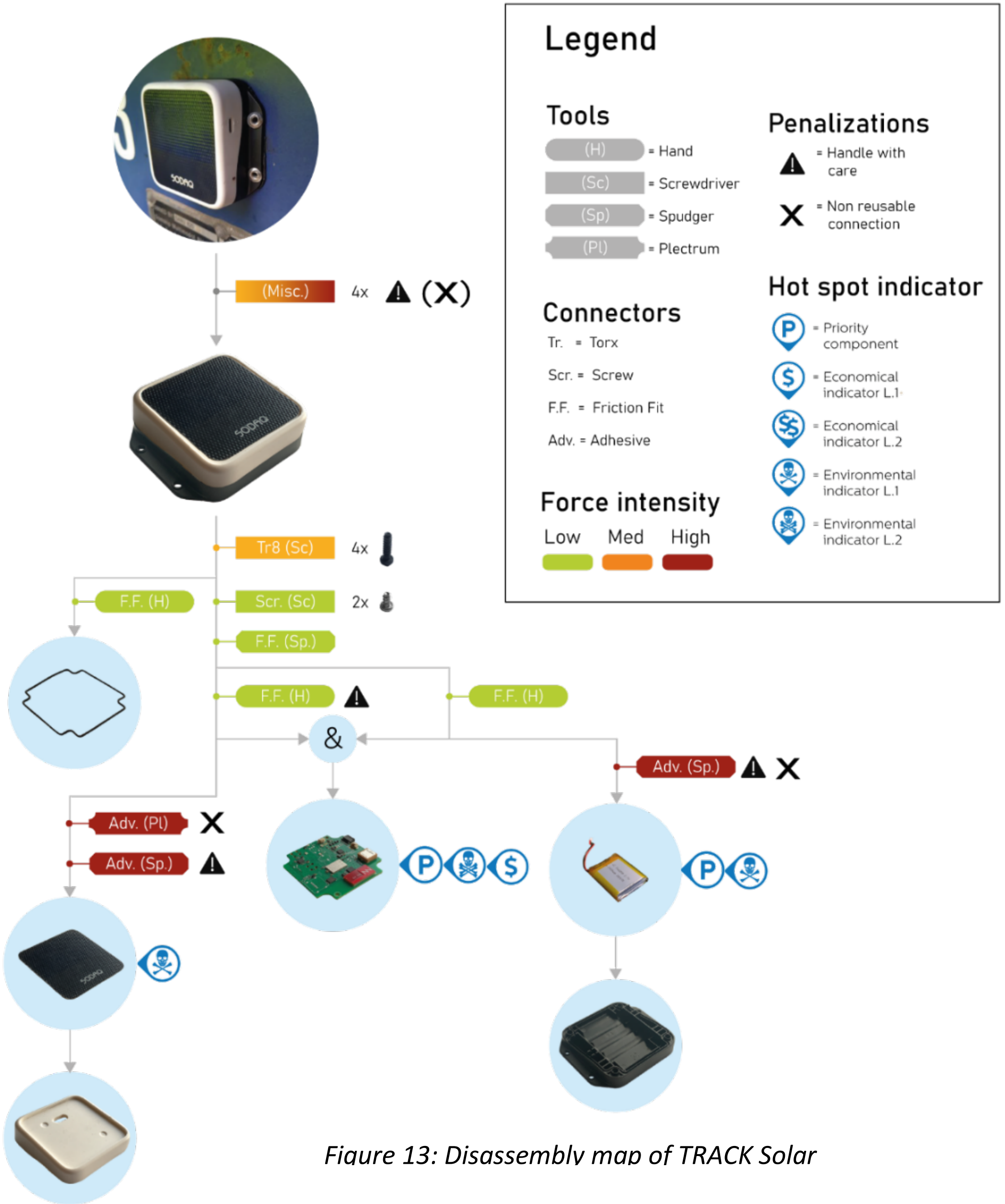


Figure 13: Disassembly map of TRACK Solar

3.3 Circularity assessment

To design for a future circular business model it is necessary to know what the requirements for the different loops should be and to what extent the TRACK meets these requirements already.

Method

To this end a list of assessment criteria was compiled based on 12 sources that provide design guidelines for each loop.

Goal

The goal for the redesign is to have a score of at least 75% on the relevant circular loops. To reach this goal the most important redesign opportunities are listed for each loop in figure 15.

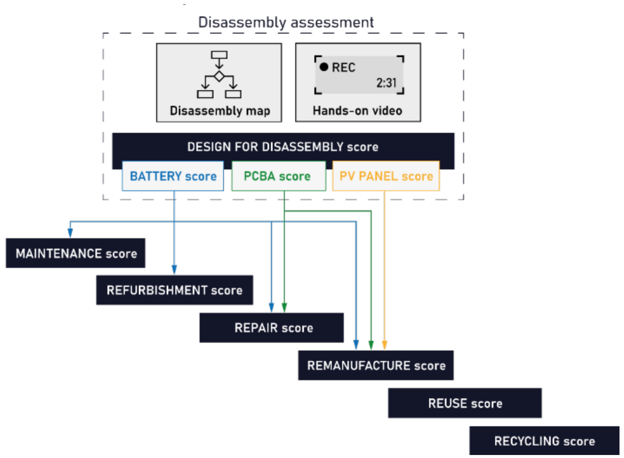


Figure 14: Circular assessment structure

Maintenance - Keep
- Identifier for documentation
- Easy to clean enclosure

Redesign opportunities
- Make battery replacement easy by designing the assembly with common tools in mind.
- Rethink the business model to ensure availability of spare batteries for the expected lifespan of the product
- Monitor battery condition and predict replacement

Repair - Keep
- Durable enclosure material
- Good visibility of fasteners during (dis)assembly

Redesign opportunities
- Implement product diagnostics to determine condition of parts
- Improve access to parts such as battery
- Use fasteners that allow for multiple (dis)assembly cycles
- Reduce number/type fasteners

Reuse- Keep
- The reusable mounting options

Redesign opportunities
- Discontinue riveting option
- Reduce the number of mounting points if possible
- Gain insight into the predicted remaining lifespan after the first use cycle

Recycle - Keep
- Recyclable enclosure material

Redesign opportunities
- Retrieve information about additives and minimize them
- Avoid the use of adhesive tape
- Define product passport requirements
- Make battery quickly accessible
- Investigate alternative components that are better to recycle (e.g. PV panel and PCBA)

Figure 15: Circular assessment results per loop

3.4 Circular business strategies

Transitioning from a linear sell-more-sell-faster business model to a circular model requires SODAQ to review its business strategy. But how can the circular loops from section 3.3 be incorporated, such that it makes not only environmental sense but also business sense and how will a new business model provide value for SODAQs clients?

Closed loop process

In a circular business model there are three points where value can be captured (TU Delft, 2020) shown in figure 16:

Acquisitioning – Acquiring the right volumes of products, parts and materials of the right quality.

To guarantee acquisition of TRACKs in the future, the contract with the client should include a take-back agreement. This agreement can be coupled with a trade-in value or an upfront deposit.

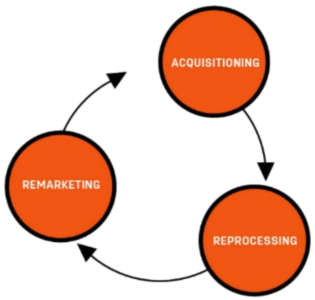


Figure 16: Closed loop process

Reprocessing – The value of the acquired product, part or material is then raised through one of the following reprocessing steps:

- Repair
- Refurbishment
- Remanufacture
- Upgrading
- Recycling

An opportunity for the reprocessing step could be automation of (parts of) the disassembly process. As disassembly can be a labour intensive and thus a costly process, the cost can be lowered by using specialized equipment (see figure 17) or by leveraging robotics and machine learning technologies based on the information from for example a digital product passport (Meloni, 2018).
Another opportunity is to outsource the reprocessing steps to a specialized company for example the analysis, repair and refurbishing of KPN modems by a third party (Drake & Farrell, 2017).

Remarketing – Finally market segments for the reprocessed products or material need to be identified.

An option for remarketing reprocessed TRACKs is cascading: reposition the product from targeting a high-end to lower performance applications till it eventually reaches end-of-life (EoL). At the EoL stage, the components can be remarketed towards recyclers for application in a future SODAQ products (Meloni, 2018).

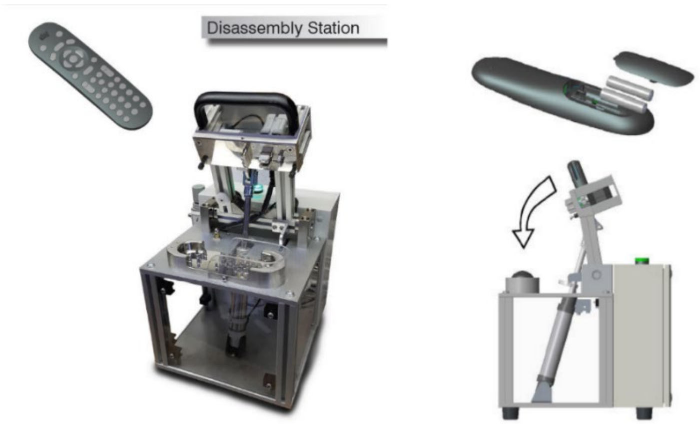


Figure 17: Disassembly station for a TV remote (D'Andrea & Evers Design)

Value propositions of circular business models

In a traditional linear business model value is created by the sell-more-sell faster principle, a concept that has been the basis for financial success of companies up to now. However the fact that society has reached or even crossed many planetary boundaries shows that this model cannot be sustainable. For companies to move from short term financial benefits to long-term value circular business model need to be considered. Typically the return on investment for these models might not be directly obvious, but in general three ways to capture value in a circular business model can be distinguished (TU Delft, 2020):

Business value

- Access to new market segments, creating opportunity to gain market share
- Access to lower-priced products or parts
- Lowering the sourcing risk through access to used products and through harvesting of parts

Customer value

- Opportunity to provide extra service during trade-in process
    - Trade-in value will create customer loyalty
    - Sustainable alternatives can be offered
- Brand protection as the company keeps control over its product

Information value

- Insight into the wear of products or parts and their expected lifespan
- Insight how the product is actually used by clients and translate this knowledge into a more targeted redesign of the product according to the needs and desires of the client

Circular business model archetypes

Next to the general ways to capture value, certain business model archetypes exist where the specific value creation opportunities are integrated into propositions (Bakker, 2019):

- **Classic sustainable model:** Sell a high-quality product at a premium with an aftermarket sales channel for extra service and a way to monetize maintenance.
- **Hybrid model:** Sell an affordable high-quality product and finance it by selling consumables.
- **Access model:** Sell the opportunity of using a product for a given time.
- **Performance model:** Sell a performance metric or result rather than a pre-determined product.

Product-service system archetypes

In both the **access model** and the **performance model** the product is part of a product-service system (PSS). In a PSS ownership shifts from the client to the service provider. In theory PSSs are an ideal way to unite sustainability and profitability, as the service provider, now the owner of the product, has a direct interest in the performance of the product. With ownership comes responsibility and a concrete incentive to minimize material use, while at the same time striving for maximum product lifetime. However, whether a PSS has a lower footprint in practise depends on whether the PSS is indeed less material intensive and whether actors in the chain can also be tempted to achieve the same result with less resources (Tukker, 2004). PSSs come in 8 different flavours (as summed up in the lower blocks of figure 18), each one increasingly more depended on the service aspect rather than on the distinctive physical characteristics of the product.

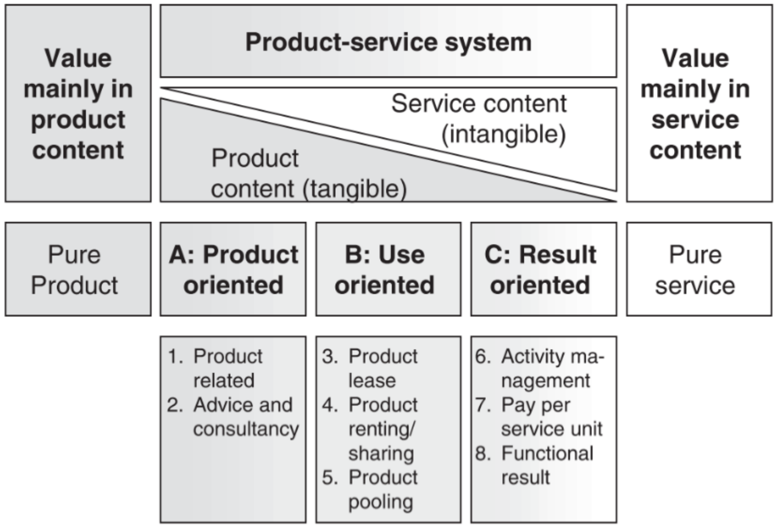


Figure 18: Product service systems overview (Tukker, 2004)

TRACK product-service system analysis

In case of SODAQ, a PSS would be a ‘Location-as-a-Service’ (LaaS) model with the physical product (TRACK) as an enabler. A more service oriented business model could be a good fit as SODAQs clients are not necessarily interested in the physical tracking product; rather in the result it delivers. The total cost of ownership (TCO) and therefore the expected cost per location message is decisive in a B2B tracking product. This makes that SODAQs circular business model might need to become more ‘use oriented’ or even ‘result oriented’ instead of ‘product oriented’.

With the product in its current form and the current use cases in mind there might be a few constrains. Because the product is securely mounted to or partly integrated into an asset, **product sharing** or **product pooling** models therefore becomes very challenging. Although these models are might not be directly applicable, the TRACK itself could enable sharing and renting business models indirectly for the assets it is attached to.

An **activity management** business model can be very hard to move into. This would imply that SODAQ would need to take over (part of) the management of the logistical operation or assets of its clients to be able to offer them (or their clients) efficiency gains. This move will likely not be welcomed by its clients, as SODAQ starts interfering or even competing directly with their core business. Besides, it would be very complex for a new inexperienced player like SODAQ to move in this very crowded and low margin business segment.

The **pay per service unit** business model on the other hand is more relevant. It is also likely more relevant for SODAQs clients than **product lease**, as they are not especially interested in the product itself.

In case of achieving the **functional result** business model, SODAQ might need to move into the asset insurance business. This fundamentally changes the business model and has to anwer such fundamental questions that it is considered to go beyond the scope of this project.

Existing service elements

In the asset tracking ecosystem of providing location data some service elements already exist. For example for the TRACK to operate the client needs a data plan with a mobile network operator and the location data needs to be stored in the cloud. There is an option to bundle both services with the 'location tracking service'.
Furthermore the client has service contracts for the maintenance of the assets. It will be convenient to bundle maintenance of assets and TRACK.

Business model proposals

There are two circular models that are relevant for SODAQ, illustrated in figure 19:

1. **Classic sustainable model**: expand the current model with an aftermarket sales channel for offering replacement parts. This is the bare minimum that should be achieved to make a circular product happen. This should be coupled with a take back agreement that SODAQ takes care of the reprocessing of non-functional products either themselves or by a specialized company.

2. **Performance model (LaaS)**: Ideally SODAQ would switch from selling physical tracking product to pay per service unit model. This means selling position information per a predefined contract period without directly selling the physical product.
   It is clear that there are synergy opportunities with other partners in the supply chain, it is therefore advised to explore the potential of a cooperation initiative to provide a better service proposition.

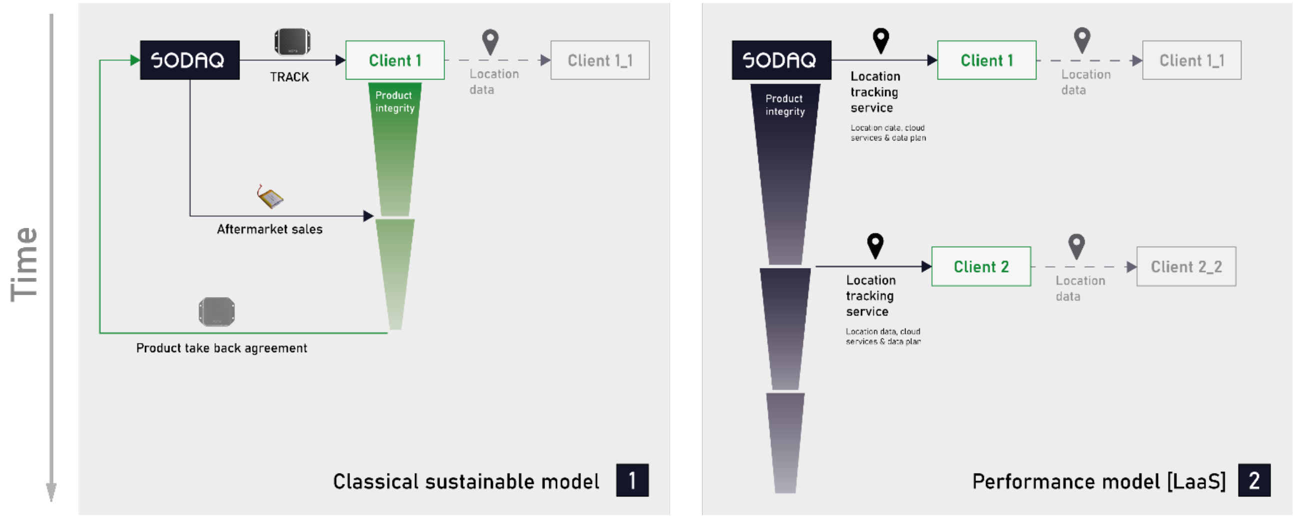


Figure 19: Proposal for a more circular Business model for TRACK with value streams over time

3.5 SODAQ business model discussion

With the two preferred business models and the circular loops on the table it is possible to discuss which direction SODAQ thinks would be the most relevant. To this end the implications of the loops for the a circular business model for the TRACK are discussed with the co-CEO of SODAQ. The following conclusions are derived from this discussion.

Conclusion of discussion

Positive market dynamics for more circular IoT
After presenting the different aspects of a circular business model the chances of success in case of the TRACK were discussed. SODAQ was open to switching to a more circular business model for the TRACK and did expect there to be a market for more sustainable alternatives (refurbished TRACKs) in the future, mainly stimulated by increasingly strict regulations, public demands and people getting more familiar with the concept of refurbished products (e.g. smartphones). Already, he noticed companies in the more restrictive building sector moving away from ownership of products due to registration of the footprint of their operations.

Risky performance model
The most fundamental decision for the company to take is whether the business model would switch to a PSS. Although the co-CEO was open to the take-back scheme, he did not yet dare to take the step towards a PSS.
His main concerns were citing liability and risk issues. He acknowledged that they copied Apples' Universal agreement of providing limited warranty for 1 year (instead of the mandatory 2 years in the EU).
Furthermore he argued that it would be very risky to offer the TRACK in a service model as they do not have sufficient experience with the current product lifetime to be confident enough that it will be profitable on the long term.

Classical sustainable model
The co-CEO suggested some sort of compromise where SODAQ would 'sell' the product with its current limited warranty to the client, while ownership stays with SODAQ, meaning that SODAQ takes care of the non-functional devices. He stated that more clients would be very willing as they do not need to include the products for the calculation of their carbon footprint in the near future.
This proposal comes very close to business model 1, the classical sustainable model, however in this case ownership would not shift to the client. It remains unclear how the risks are shared in this case, for example when accidental damage occurs.

Maintenance
Maintenance of for example the battery could very much be an option if performed by the technical staff of the client to save on reverse logistics costs.

Reuse
Reuse is also attractive as long as the product can be shipped directly to from the old client to a new client. In this case putting in a fresh battery would also have to be done by the old client.

Repair & remanufacturing
The co-CEO expects the cost of logistics and reprocessing by SODAQ or a third party would likely be much higher than its potential margin. Furthermore at the end of the first use cycle, the product might either be

no longer supported by the network operators or no longer competitive even at a reduced price.

Upgrading
Currently SODAQ is still facing a design for availability challenge. Which means components Partly because of lock-down regulations in China, partly because of suppliers halting production for older generation electrical components. The co-CEO expects a complete redesign of TRACKs PCBA is required every 3 years. Preparing for and managing of upgrade cycles of the PCBAs will become quite complex and might add unnecessary cost. It could be easier to replace the complete PCBA.

Recycling
The co-CEO did see most potential in closed loop recycling and the use of recycled materials, especially in the enclosure. There might be enough value captured when reselling the materials or components to recyclers. Furthermore the marketing aspect of the recycled plastic 'look and feel' was seen as an effective marketing tool by the co-CEO.

Business model conclusion

Business model

The LaaS business model was perceived as too risky for a company such as SODAQ therefore the **classical sustainable model** would be a better fit.

Focus loops

Currently, SODAQs co-CEO did not yet see a good business case for repair, remanufacturing and upgrading of the TRACK.
According to him the focus should first of all be on (closed loop) **recycling** and **maintenance**.

3.6 Circular redesign focus areas

Design for maintenance and reuse are preferred

In a circular business model, the reprocessing steps that will bring the product back to highest level of product integrity with the lowest cost are preferred. These reprocessing steps are maintenance, repair and reuse and should be the initial focus loops for the redesign.
The co-CEO also saw potential for maintenance and reuse loops in the form of a battery replacement by the technical staff of the client, while repairs and upgrades would need to be performed by SODAQ or a third party, which is not considered viable for this product.

Design for disassembly as enabler for circularity

For a circular business model a quick and non-destructive disassembly process is essential. To identity potential areas for improvement in this process the disassembly map was used.
The disassembly map of the TRACK shows clear improvements for finding an alternative for the difficult to remove adhesives tape connections and decreasing the disassembly depth of the battery.
This focus area will be particularly important for redesigning the product for quick maintenance of the battery.

Importance of *Design for recycling*

Recycling on the other hand is situated at the bottom of the hierarchy, and is considered to be a 'last resort' as the product integrity will be lost fully. However, chapter 2 shows that design for recycling is essential for lowering the sourcing impact of the product in the future. Additionally, focussing on the recycling and the use of recycled materials plays a main part in the co-CEOs vision for more 'World friendly' products.
Currently, the (mechanical) recycling potential of the TRACK is already close to the defined target value of 75%. However, the use of adhesives still results in a low recovery rate of the materials in practise. For example the large surface area of the adhesive of the PV panel makes it impossible to liberate the component from the top enclosure material without contamination.

A circular future is difficult to envision

Both SODAQs co-CEO as the hardware engineers are critical of the range of potential business opportunities of preserving the product integrity such as the possibility of upgrading an obsolete network component. Both cite the cost of reprocessing as a showstopper. Furthermore switching to a service model in which long lasting product design is more valuable is considered to be too risky for such an unproven product.
However there cannot be a truly 'World friendly' product without incorporating the principles of circular product design. The best way for designers might be to trust the theory and what this potential circular future could actually look like. This means make it physical and make it visual and show how it would work in the future context

4 PRODUCT REDESIGN CRITERIA

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As a conclusion from the product analysis of chapter 2 and circular product analysis of chapter 3 the following program of requirements and wishes is collected to inform the redesign.

	KEY FUNCTIONAL REQUIREMENTS
0	Redesign meets requirements of current product (see section A1), with the most important:
1	Protect the electronics for at least 7 years from wear through environmental and use context factors and it is therefore essential that the current IP67 rating is not compromised
2	Enclosure material should not impact the antenna performance, hereby minimizing the energy consumption, which will lead to either longer autonomous operation or to a smaller battery and PV panel and hence lower impact of the electronics.
3	Ground plane length of at least 70 mm. This makes that the ground plane cannot become smaller as it will affect current LTE-M antenna performance (see appendix A3)

SQ	SODAQ WISHES
1	Enclosure is made out of recycled plastic or at least a recycled fraction
2	No additional parts (currently three for the TRACK Solar) are required for the redesign to keep investment cost of moulds low
3	Environmental Impact of the PCB is lowered without impacting performance
4	Product enclosure communicates the world-friendly vision through Colour, Material, Finish (CMF) (see for guidelines appendix H6)

DY	KEY DISASSEMBLY WISHES
1	The enclosure can be disassembled significantly faster to provide access to the electrical components for future maintenance and repair actions and give good working electronics a new life.
2	All components are directly accessible after opening
3	All connections for components are approved for manual liberation (see appendix D5), so no 3M adhesive tape for the battery and PV panel
4	Disassembly can be performed by technical staff of the client.
5	Disassembly can be performed without tools or with a single basic tool (from the list of appendix D6)
6	All connections are reusable
7	Parts can be secured directly upon insertion without any extra operations (e.g. screwing, tightening or gluing)
8	Redesign meets most (>75%) of the remaining guidelines provided in appendix X

ME	KEY MAINTENANCE WISHES
1	Diagnosis by a signal that can be understood without the need for any supporting documentation or software
2	Business model should allow for availability of spare parts over the expected average durability of the product (5 years)
3	Redesign meets most (>75%) of the remaining guidelines provided in appendix X

RE	KEY REUSE WISHES
1	Mounting connection should be reusable
2	Find a solution to determine the remaining lifetime of the product and/or its components
3	Reduce the number of mounting points to make dismounting faster and more attractive

RG	KEY RECYCLING WISHES
1	Closed-loop recycling of components and materials
2	Avoid the use of adhesive tape
3	Build a framework for a product passport
4	Make the battery easily accessible
5	Redesign meets most (>75%) of the remaining guidelines provided in appendix X

5 FUTURE SUSTAINABLE TECHNOLOGY ANALYSIS

Based on the findings from chapter 2 the problem definition was redefined and the goal of a ‘world-friendly’ redesign has become the reduction of the CO_2 impact per message through lowering the impact of the electronics.
In chapter 3 the circular opportunities for extending component life through the preservation of product integrity and the inertia principle are discussed. Extending component life is one way to lower the impact per message as more messages could be send during the lifetime of the components.

This chapter is aimed at reducing the impact by applying lower impact materials & production processes and questioning whether components such as the battery can be avoided.
This is done by looking at broader industry developments to see what is coming and researching alternative components that aim to address the (wide spectrum of) sustainability issues raised in chapter 2 or support a more circular business model.
At the end a future vision for the TRACK is created using the developments in the following areas:

- Localization & communication technologies
- Sustainable PCBA design
- Energy harvesting technologies
- Plastic recycling technologies

5.1 Communication & location technologies

SODAQ as early adopter

As the product analysis showed, the communication and location technologies essentially define the product. It is therefore not surprising that new business opportunities arise when new network technologies are rolled out by operators. For example it could provide products with longer battery life or better network coverage.
When putting SODAQ product introductions side by side to introductions of network technologies in figure 20, it becomes clear that SODAQ is an early adopter of new networking technologies. This stems from the days that SODAQ used to sell developer boards with the mission to make new networking technology accessible to developers, makers and enthusiasts, often keen to test out these new technologies as soon as possible.
To see what role new networking technologies could play in the future of the TRACK line, this section aims to provide an overview of the relevant technological developments

Now: LTE-M

Starting off with TRACKs current primary networking technology: LTE-M (long-term evolution for machines). LTE-M is based on 4G cellular technology and therefore more widely adopted, compared to other more specific networking technologies for the IoT market: LoRa and NB-IoT (figure 20). LTE-M also has a higher bandwidth and is able to support data transfer when in motion. LTE-M can also provide higher data rates than LoRa, allowing more data to be send per message. (Vodafone, 2023)

Next: LoRa Satellite

Over the last years the number of non terrestrial network providers is growing. The first non terrestrial networks aimed at IoT market utilize the LoRaWAN standard and this network type is generally referred to as LoRa Satellite. The benefit of using satellites for the TRACK instead of terrestrial ground stations is the ability to provide worldwide coverage at a relatively low cost; the satellite is only the size of a shoe-box (Lacuna Space, 2023).

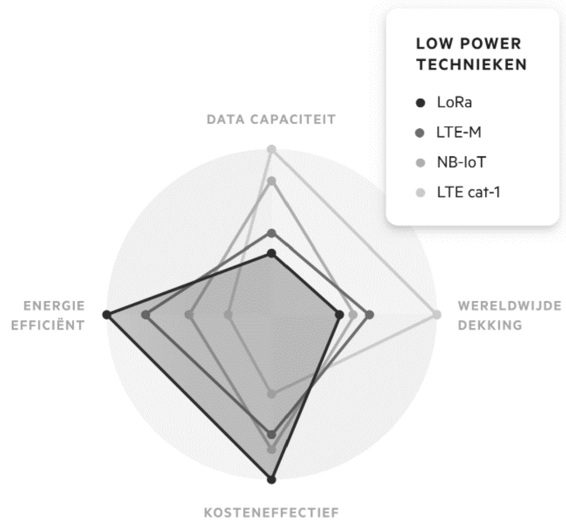


Figure 20: Comparison chart of common low power networking technologies (KPN, 2022)

Next: 5G Advanced

Accurate positioning

Currently accurate positioning of the TRACK is done through Wi-Fi (indoors and urban areas) and GPS (outdoors and rural areas).

5G Advanced aims to combine both efficient data communication as well as accurate positioning indoors and outdoors. Nokia claims that 5G Advanced would be able to offer sub-10cm position accuracy due to the use of a technique new to terrestrial networks, called "carrier phase positioning" (Nokia, 2022). With the current proof of concept prototype, the position of an asset in a factory could be located down to 50 cm accuracy 95% of the time (Henninger, 2022). So potentially a next generation TRACK would only need to have a single 5G Advanced antenna, which could save on the amount of electrical components (ICs such as SoC, GPS antenna, modem).

Reduced Capability devices

While 5G is has been on the market for some years now it has not been used for low power applications such as IoT. With the introduction of 5G Advanced the goal is to expand the target market of 5G to lower power (IoT) applications (i.e. devices with reduced capabilities or RedCap) and even passive IoT, that will use RF energy harvesting (see section 4.3). This is made possible through complexity reduction measures and new power saving features (e.g. low-power wake up signal) (Nokia, 2023),(Qualcomm, 2022). However, without exact specifications it is difficult to say to what extend battery life of the TRACK could be improved by using 5G advanced.

Non-terrestrial networks

Full integration of non-terrestrial networks with conventional terrestrial networks is expected to come with the introduction of 5G-Advanced. Non-terrestrial networks can offer data communication worldwide using satellites or high-altitude platform systems such as unmanned airships, airplanes above 20 km and unmanned aerial vehicles (UAV) such as drones. As with LoRa satellite this can be especially relevant as TRACKs may operate in areas without cell tower coverage (Nokia, 2023).

Future: 6G

Network as a sensor

6G is still far out into the future and current research and discussions about specifications are still in early stages. Yet one of the main elements of 6G network technology could potentially have a big impact on location tracking services. This aspect is called 'Joint Communication And Sensing' (JCAS), which means that 6G networks will be using the same spectrum both for communication and sensing purposes, essentially turning the whole network into a sensor and hereby enhancing future applications with a digital 'sixth sense' (Nokia Bell Labs, 2021). This means that objects or users that need to be localized no longer need to carry an active 6G device.

Massive digital twins

JCAS is part of a future vision in which 6G sensing, in combination with other IoT sensors, is used to create digital copies of the physical world (Nokia Bell Labs, 2021). This results in interactive 4D maps of whole cities that are precise in position and time and can be accessed by a large number of humans and machines for planning of activities (Ericsson, 2023).

Radar-like sensing

In the basis 6G network sensing is a radar-like technology, made possible by exploiting new higher frequency bands (from mmWave to sub-Terahertz), a wider bandwidth and a denser distribution of massive antenna arrays (Huawei, 2021).

Much like radar, sensing of an object can be done by detecting how the emitted radio signals have bounced off of objects in the environment. The received signal can contain the following information (Ericsson, 2021), (Nokia Bell Labs, 2021):

- 3D location and size of the object by using time-of-flight of the signal
- specific shapes (e.g. sphere or flat plate) using ultrawideband radar
- speed of movement by measuring the doppler shift of the echo (figure 21)
- (Potentially) material properties by measuring the reflected signal power which is different per material type

To sense objects in the environment, beamforming will be combined with beam sweeping. Using advanced signal processing, with the power of AI/ML algorithms and object classification, and by combining signals of different bands (multiband sensing), multiple objects can be detected and identified at the same time.

Finally as with radar, the 6G network sensing will also work in smoke, fog, dust and darkness, although with degraded performance, and it can be used in places where, for privacy reasons, cameras aren't allowed (Nokia Bell labs, 2021).

Sensing as a service

The advantage of JCAS is that it makes use of an infrastructure that will be rolled out primarily to serve communication over 6G. Hence, the sensing will come as an additional service and almost 'for free' to mobile operators alongside communications (Ericsson, 2021). The question then is, if it will become a reality, how SODAQ will be able to capture the value of such a service in a future, where active localization devices (i.e. asset trackers) are no longer needed.

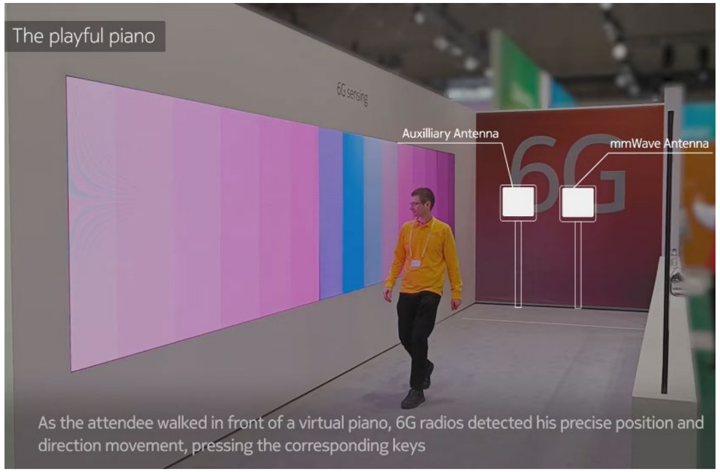
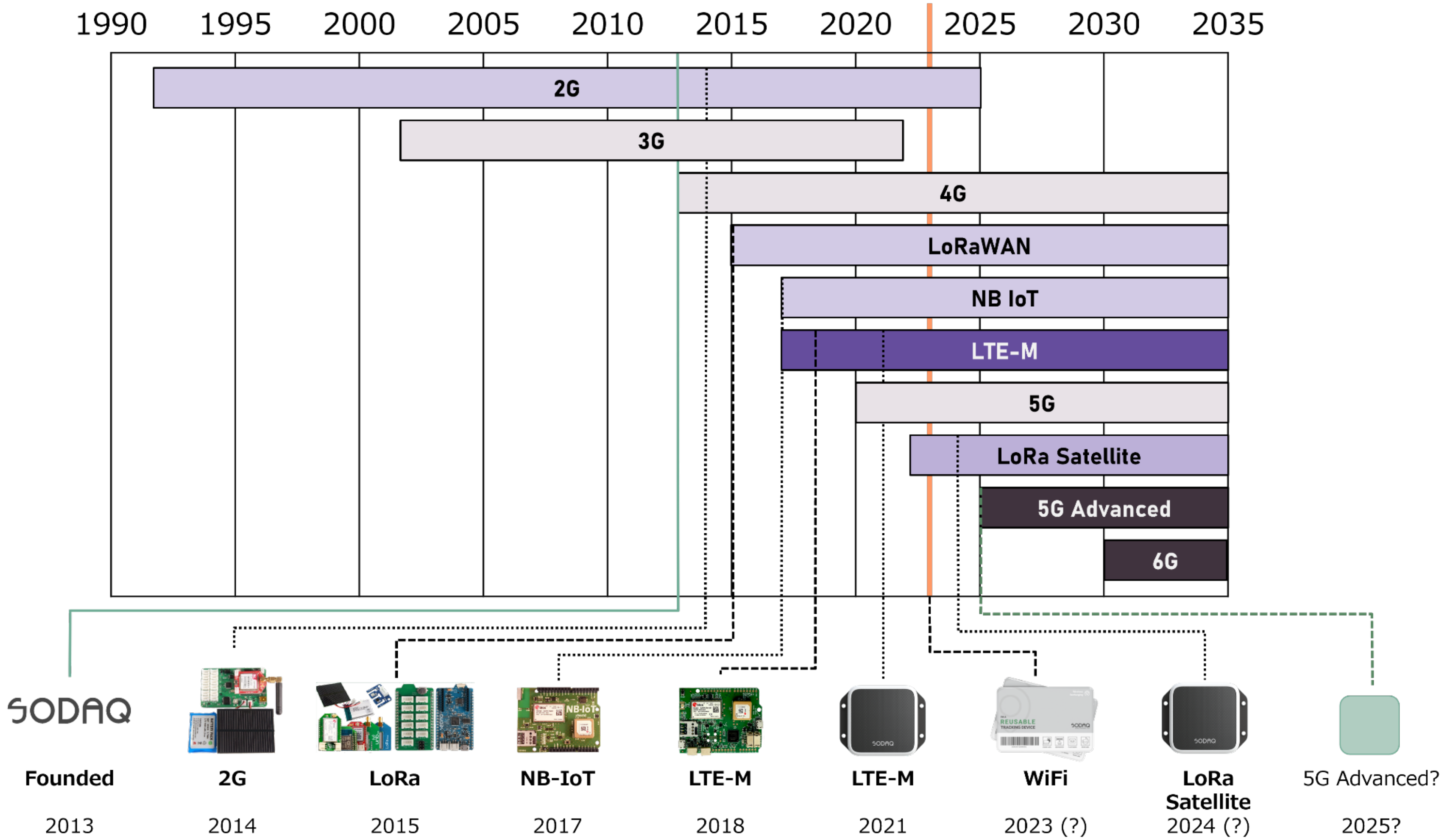


Figure 21: The playful piano 6G sensing demo installation at MWC 2023 (Nokia Bell Labs, 2023)

Conclusion

- LoRa satellite has potential for a future TRACK as this might bring worldwide coverage at relatively low cost. However the LoRaWAN standard does not offer the same data capacity as LTE-M, so performance will be reduced.
- 5G Advanced offers the same benefit as LoRa satellite with the integration of NTN networks in the 5G Advanced standard. But 5G Advanced has the additional sustainability benefit of using fewer electronic components through combining precise worldwide localization with a data component. 5G Advanced is promised to be more suitable for IoT devices compared to 5G, however details are still scarce.
- 6G JCAS has the potential to redefine tracking, no longer requiring an active tracking device like the TRACK. Further research into the implications of the development for SODAQs business model is therefore advised

Communication & location technology roadmap



Sources: 2G (VTM, 2023), (Prepaidsimkaarten.nl, 2023), 3G (NU.nl, 2018), 4G (Emerce, 2013), LoRaWAN (BTG, 2015), NB IoT(Premium), (Vodafone, 2023), LTE-M (PrepaidSimkaart.net, 2018), 5G (NU.nl, 2018), LoRa Satellite (Lacuna Space, 2022), 5G Advanced (Nokia, 2022), 6G (Nokia, 2023)

5.2 Sustainable PCBA design

According to the TRACK LCA and literature sourcing and production of the PCBA is the most impactful part. This is mainly due to the production of highly complex ICs and toxic PCB production. In this chapter the future developments around more sustainable production methods, lower impact materials and options for recycling are discussed.

PCB vs 'real' PCB

Although 'Printed' is part of the term Printed Circuit Board (PCB), it does not make much sense for contemporary PCBs. A better term would be Etched Circuit Board; as producing a PCB is mostly a subtractive process involving toxic etchants.
Consequently, circuit boards made by an additive process of printing with conductive inks are often referred to as 'real' or 'fully' Printed Circuit Boards. To avoid confusion, the term Printed Electronics (PE) or Flexible Printed Electronics (FPE) is used. Printing of electronics is mostly performed Roll-to-Roll (R2R) on a flexible substrate which can be up to 15 times thinner compared to conventional FR-4. Moreover, FPE should not be confused with Flex PCBs. Flex PCBs are PCBs manufactured using the traditional subtractive method, but with flexible substrates such as Polyimide (PI).

Current Drivers of PE

Printed Electronics is not a new concept, looking at the history of PCB development in appendix F1. The sustainability argument was one of the reasons for the revived interest in the production technology, however nowadays it is no longer the only reason as there seems to be a market push. Three drivers for the development of the PE and additive manufacturing (AM) technology can be identified:

1. PCB Reshoring

European PCB manufacturers have been outcompeted by Asian players for some time now. In 2015 the European players contributed to only 4% of the worldwide PCB production (Gasch, 2016). Since then the number of companies in the EU has further dropped by nearly a third from 247 to 171 companies in 2021 (Read, 2022). Provided that 2021 is a year of significant demand for electronic components due to consumers buying more electronic gadgets during COVID lockdowns, it is clear that the downward trend is likely to continue if no concrete action is taken.

The case of Nokia illustrates this point. Since the offshoring of Nokia's electronics production facilities from Finland to Asia since 2005, former Nokia employees with industrial experience in the mobile phone and ICT production have started looking for new opportunities. Together with knowledge institutions some of them set up the PrintoCent program with the goal to accelerate the industrialization of the then upcoming Printed Electronics (PrintoCent, 2019). Nowadays the PrintoCent industrial cluster consists of approximately 40 companies that cover different parts of the PE value chain (from the material manufacturers to the product integrators like Nokia) (PrintoCent, 2023).

The EU has also acknowledged that PE can be of interest for a competitive European industry and it is therefore part of the Advanced Technologies for Industry (ATI) project. The ATI project focuses on the advanced technologies that will enable and help industries to successfully manage a shift towards a low-carbon and a knowledge-based economy. (European commission, 2023).

"For Europe it is important to build on current strengths and capitalise on its strong research and innovation position. This requires commercialisation by businesses in Europe, which are currently small-sized. Further upscaling of these businesses is required to gain a strong position in the market of flexible and printed electronics. This could be stimulated with targeted investments in specific application areas
for flexible electronics" (Scholten, 2021)

This means that it might be possible for SODAQ to apply for EU funds to reduce the investment cost for prototyping new PCB designs using PE.

2. New product categories

Currently there are several products where PE is used rather than the conventional method:

- **RFID tags** – The most important benefit of printing is the opportunity for low unit cost due to high volume fabrication of the simple single layer circuits.

- **OLED display technology** – PE provides opportunities for printing on extremely thin flexible substrates (flexible displays), a inkjet printhead enables easy scalability of substrate sizes and PE enables a high-efficient production process without material waste (JOLED, 2023).

- **Thin film PV cells –** Printed PV cells can be made with low impact materials and in a high speed R2R processes. See chapter 4.3 for more detail.

3. PE Sustainability

Although sustainability is yet to become the main driver for the technology, this would be an incentive for SODAQ to investigate the transition to an additive production method. Applying an AM method the LCA of a PCB shows that the impact cradle to gate can be reduced 75% (Elephantech, 2022) - 86% (Nassajfar, 2021) compared to a traditional FR-4 PCB design.

Furthermore PE provides the following sustainability benefits (PrintoCent, 2019):

- Material consumption is very low – often only very thin layers, printing methods are additive resulting in minimal process waste, materials can be recycled in the production process
- Production process without hazardous chemical waste
- Production process uses little energy – mass production, mostly at room temperature
- Production is done in most cases in normal atmosphere and clean room is not needed
- Products are often thin and lightweight, which saves fuel and space required in transportation of the product
- The choice of using different materials as inks and substrates, biodegradable/biobased/recycled/recyclable materials are available in many cases
- The housing of the product can be used as substrate to save additional material
- Production process can be chosen to match the required volume and market demand, and local production is possible
- The manufacturing technology allows rethinking of the product design to minimise e.g. the size of the product or waste generated

Flexible Hybrid Printed Electronics

A new upcoming sub-genre in the field of FPE's originates from the introduction of Surface Mount Technology (SMT) from traditional manufacturing to the field of FPEs. By taking the lower impact, higher throughput production methods of FPEs and couple it with the processing power of SMT components (such as ICs), a new hybrid form is created that aims to combines the advantages of both (as illustrated in figure 22). PCBs manufactured using this production process are therefore referred to as Flexible Hybrid Electronics (FHE) (Khan, 2020).

Reflow soldering alternatives

Reflow soldering can be a an energy intensive process as determined in chapter 2.6. With FHE gaining traction using traditional reflow soldering is no longer possible as flexible substrates like PET cannot withstand the high temperatures, therefore low temperature alternatives are developed.

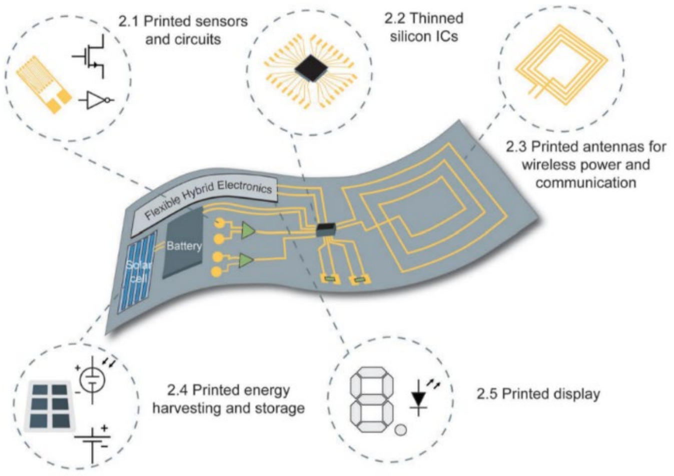


Figure 22: A Flexible Electronic system, showing the key components of FHE

Photonic soldering

One of these alternatives is photonic soldering. It uses a high-intensity pulsed white xenon (Jang, 2021) or UV light (PulseForge, 2023). The soldering works by applying the heat locally at the solder point instead of heating the complete board. Not only does this method prevent damage to the substrate, it also saves up to 85% in energy consumption and it is much faster compared to reflow soldering (PulseForge, 2023).

Anisotropic Conductive adhesive

A second replacement for soldering specifically aimed at flexible substrates is Anisotropic Conductive Paste (ACP) and Anisotropic Conductive adhesive Film (ACF) (figure 23a). This is a thermosetting resin containing conductive silver-coated glass beads, which allow for conduction in the direction perpendicular to the contact points (z-axis), but spaced far enough apart to be electrically insulating in-plane (see figure 23b).
Applying it to the substrate may be done using a lamination process for ACF, or either a dispense or printing process for ACP. Most types require both heat (100-220 °C) and pressure during the bonding process of the SMD component to the substrate for a couple of seconds. (Wikipedia, 2023)

Figure 23: (a) Anisotropic conductive adhesive film with (b) traces formed in z-direction through a magnetic field

End-of-Life reversible adhesion

Next to depopulation of the electrical components using a reversed reflow process for FR-4 PCBs used currently, there might be other techniques that make recovery of componnents and materials easier during recycling.

Temperature based adhesion

Luxembourg based LIST together with the company Molecular Plasma Group are working on a molecular coating that changes adhesion characteristics depending on the temperature. (Molecular Plasma Group, 2021) (figure 24). The coating is currently applied to composites to improve layer separation during recycling (LIST, 2022), but potentially it could be a way to separate copper layers from the FR-4 composite or copper traces from a substrate.

Water based adhesion

The water based technique the PCBA should be put in (near) boiling water after which the components can be pushed off with minimal force. There are two British companies with this technique on the market In2Tec and Jiva Materials.

In2Tec has developed the ReUSE, a set of materials and processes, which lead to a completely unzippable printed circuit electronic assembly (Hunt, 2015). ReUSE is specifically focussed on low-complex circuit assemblies which can be replaced by FHE.

Jiva Materials claims that its product, Soluboard, is the worlds first fully recyclable PCB substrate in sheet form. As its name suggest the PCB must be dissolved in near boiling water in order to remove the electronic components more efficiently during recycling (figure 25) (Arroyos, 2022).

Self-biodegradable adhesion

A range of smart enzyme-containing polymers with triggered intrinsic self-biodegradation properties. Originally developed for recycling of multi-layer packaging, but could potentially be applied to multilayer PCBs as well. (TERMINUS, 2020)

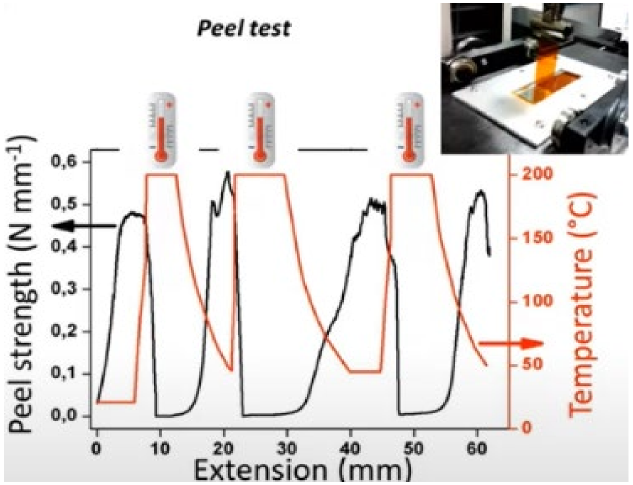


Figure 24: MPG temperature based adhesive concept

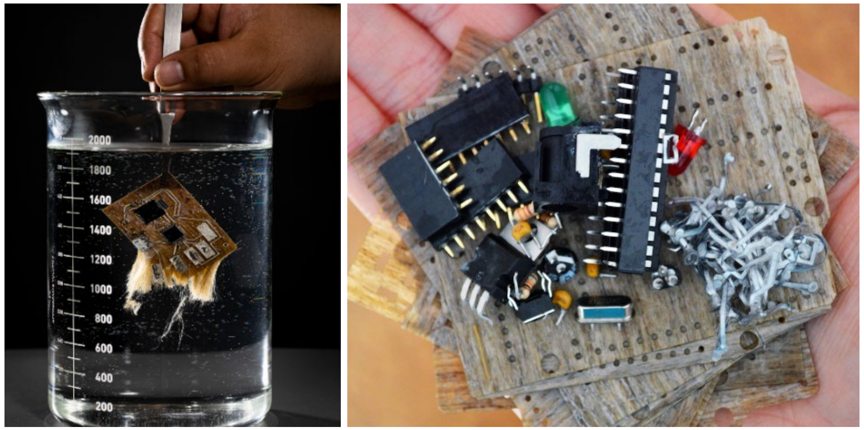


Figure 25: Soluboard component liberation method

In-mould Structural Electronics

Another direction that was also mentioned in the ‘discovery paper’ mentioned in appendix F1 is the opportunity to use the casing material of the product as a substrate to save on materials. This is called In-mould Structural Electronics (IMSE)

Sustainability

Studies show that IMSE could save up to 70% less in product weight (Simula, 2018) and 62% reduction in footprint (Muñoz, 2022) for certain applications. The IMSE can be considered an evolution of the in-mould decorating (IMD) process, in which thermoformed plastic with a decorative coating is converted to a solid component using injection moulding (IDTechEx, 2023).

Recycling issues

In the IMSE production process the electronics are fully encapsulated during injection moulding (figure 27). Thanks to the encapsulation the design will become very durable, however it makes the liberation of the electronics during recycling impossible. Currently there is no way to recycle IMSE products, but the Finnish company Tactotek expects that chemical recycling through pyrolysis will be commercially viable and plans to build its own recycling ecosystem in the near future (Tactotek, 2022).

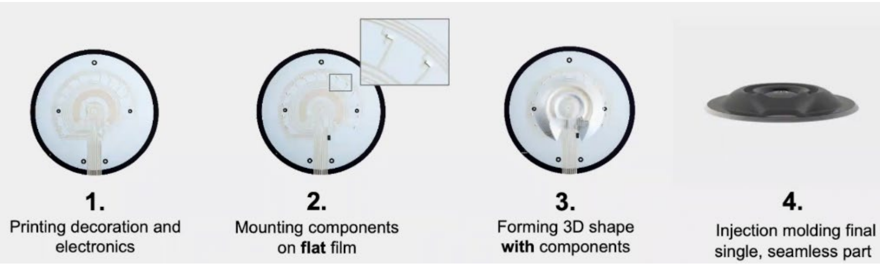


Figure 27: IMSE production process

Printed electrical components

As shown in chapter 2, the ICs are the main source of the impact of the TRACK. Looking at the IC production worldwide, it is predicted to grow 4-12% till 2030. Even with the use of more renewable energy, the emissions from IC manufacturing will still be about 3 times too high compared to the target set by the Paris accord (Ragnarsson, 2022). This means that the industry has to shift to lower impact manufacturing methods and additive manufacturing. ICs and SMT components are already showing potential for (simple) applications and are expected to become more and more competitive for more complex applications. However replacing the TRACK four layer PCBA design will take at least a couple of years.

Printed ICs

PragmatIC has developed an integrated circuit manufacturing technique that does not require a silicon wafer as a basis, but uses thin-film transistors instead (figure 28). PragmatIC claims that its additive manufacturing method is significantly more sustainable than the traditional subtractive manufacturing method, with a 1000 times lower CO2e and with 100 times less water consumption as a result (PragmatIC, 2023). PragmatIC also uses much less potent greenhouse gasses during manufacturing.

Figure 28: Pragmatic printed flexible wafer

Printed SMT components

FleepTech's PrintIC technology is relatively similar and enables the realization of an extensive range of analog and digital electronic circuit blocks, based on entirely printed Organic Thin Film Transistors (OTFT) (Fleeptech, 2023). No estimate is given about the relative impact reduction, but if all SMT components can be replaced with their printed counterparts, the assembly and reflow process can be eliminated in the future.

Photonic ICs

A Photonic Integrated Circuit (PIC) differs from traditional IC in that they use photons (light) to transmit data instead of electrons (electricity). The architecture of a PIC is somewhat different to an electrical IC, though PICs can be created by using the same manufacturing processes as for the more mature IC industry. But new materials platforms such as PICs printed on flexible substrates may emerge for some applications in the future as well (ISPR, 2019).

Key Enabling Technology

The European Commission has defined photonics as one of six Key Enabling Technologies for Europe (Photonics21, 2017) as PICs is predicted to enable significant advances in computing speed, high-speed data transfer, data integration and reducing IC form factors across industries. Currently PICs are mainly applied within the communications industry and (hyperscale) data centres (IDTechEx, 2022).

Sustainability

All in all this is a development that could potentially improve the energy efficiency of traditional electrical circuits in (more complex) future IoT products. However it is hard to tell how significant the implications of this relatively nascent technology will be for the TRACK PCBA and if it will be able to compete with traditional ICs or even printed ICs in terms of sustainability improvements.

3D printed structural electronics

3D printed electronics combine the structural parts using 3D printing with PE in a single process (figure 29) (Holst Centre, 2023).

Sustainability

- Inherent protection from dust and dirt enhances product durability
- Reduced part count by integration of functions simplifies disassembly
- Reduced materials mix simplifies recycling
- Flexibility in shape reduces material usage
- Potential for automated repair, reuse of components and product recycling

Further advantages

- Mass customization, not requiring product specific tooling
- Low cost In-house prototyping (Botfactory, 2023)
- Low product assembly cost

However production speed at high volume is still the main challenge for 3D printed components.

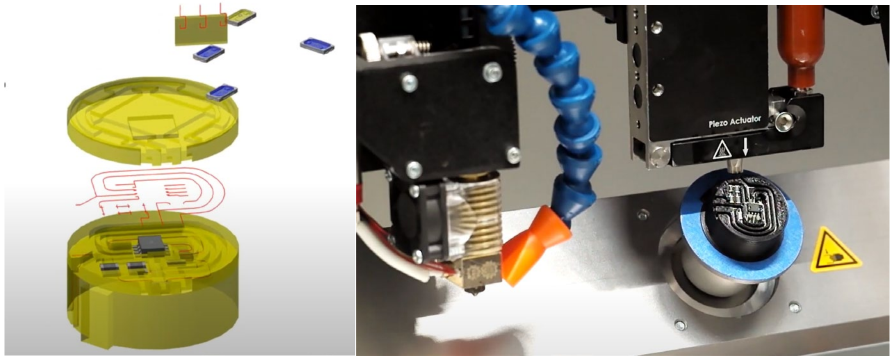


Figure 29: 3D Printed Structural Electronics Luminaire (Neotech AMT, 2021)

Conclusion

FHE as world-friendly alternative to FR-4 PCB

After the pioneering phase of PCB manufacturing subtractive FR-4 based PCB designs have achieved market dominance over additive technologies. Recently, three drivers cause PE to be relevant again: PCB reshoring, new product categories and most relevant for this project: a more circular and hence more world-friendly alternative to FR-4.

Due to the lack of interest in the technology in the past, the development of additively manufactured FHE in terms of performance, features and common development tools, is lagging far behind traditional subtractive PCBs. This limits adoption and makes it only applicable to create more simple circuits at present. The current four layer PCB design of the TRACK will therefore be very challenging and hence costly to convert to a FHE design.

Through continued development in better performance, carrying over features from subtractive PCB manufacturing and standardization of tools FHE could reach a wider market of more complex FHE designs.

Furthermore various technological developments (e.g. reversible adhesion of components and photonic soldering) and material advances (fully biodegradable PCBs) in the PE field cause the technology to have the potential to be much more world-friendly than traditional subtractive manufacturing.

Finally through experience with the FHE technology in other projects within SODAQ involving more simple circuits, it is expected that a FHE will become achievable for the TRACK PCB in the future.

World-friendly IC alternatives are gradually coming

Printed ICs and PICs both have the potential to lead to more world-friendly ICs for the TRACK, the most impactful components. Printed ICs are more world-friendly due to the focus on very low impact production and PICs due to the supposed high energy efficiency of the data processing. By making the processing more efficient it might become possible to go battery free.

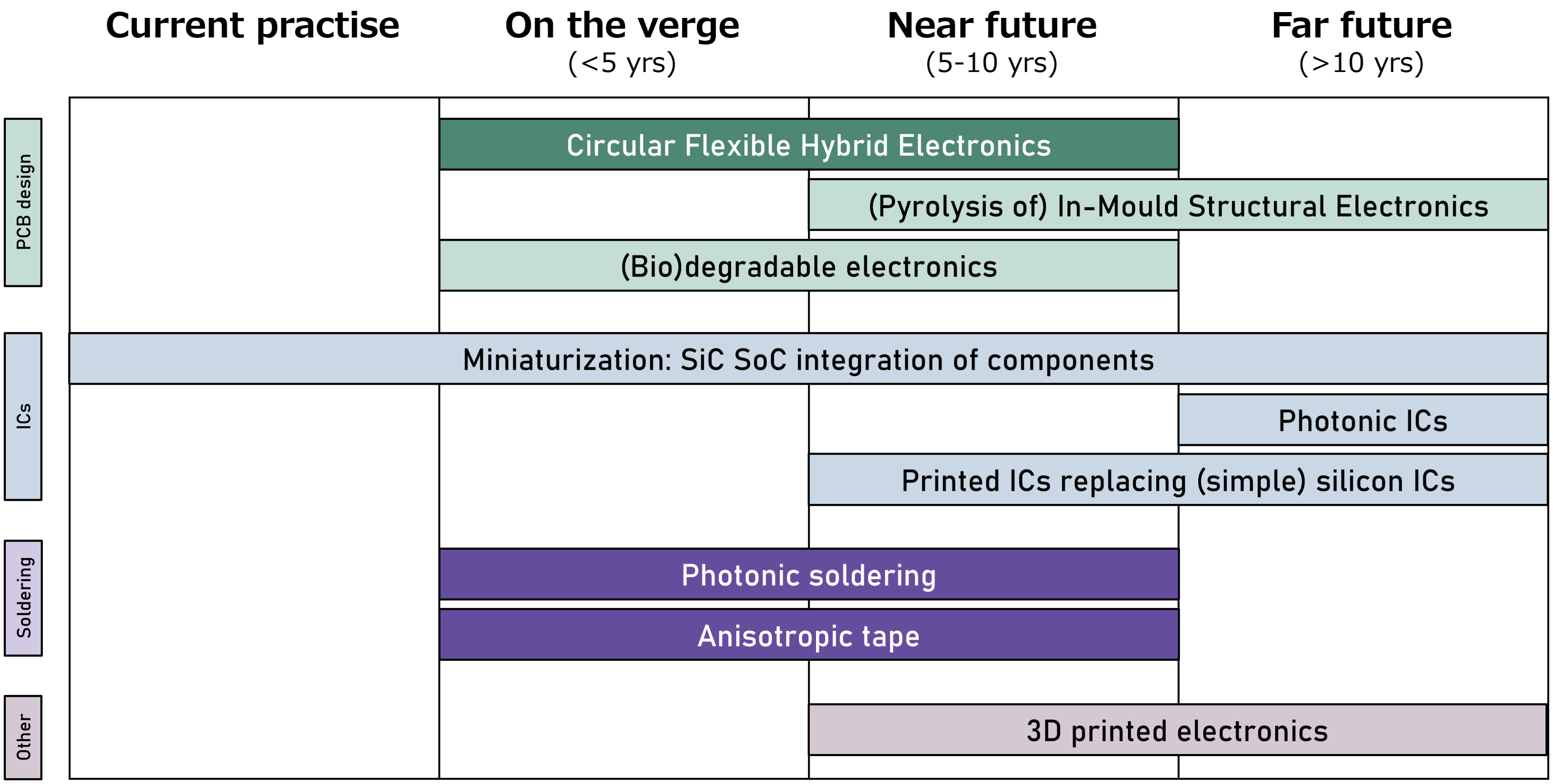
While printed IC are currently aimed at replacing relatively simple ICs, PIC are at the other end of the spectrum of replacing ICs with very high processing requirements.

As IoT devices such as the TRACK have relatively low computational power, printed ICs, which are more aimed at the lower end, have more potential to replace some semiconductor ICs of the TRACK in the near term than PICs.

Product-integrated electronics need EoL solutions to be truly world-friendly

Both IMSE and 3D printed structural electronics have a lot of sustainability potential as the integration leads to significant material and component reduction. And while it on the one hand enhances durability of the product due to the complete sealing of the electronics, on the other hand it will make recycling extremely challenging. It is therefore concerning that during the development of both production methods no real solutions are given for the effective recovery of materials and components at the end-of-life. This means that these production methods are not (yet) suitable to be used in a world-friendly product.

Sustainable PCBA roadmap



5.3 Energy harvesting technologies

The goal of the energy harvesting technology is to provide the TRACK to work autonomously, without the need for battery swapping or charging from a socket for at least 5-7 years.
Currently the TRACK is powered by a solar panel, which has by far the highest energy harvesting power potential (see figure 30). However as solar power is not always available, TRACK will currently not be able to function without batteries. Avoiding the use of LiPo batteries is part of the vision of SODAQ for more world-friendly IoT given the negative external effects from mining of the minerals, specifically cobalt (see appendix C).

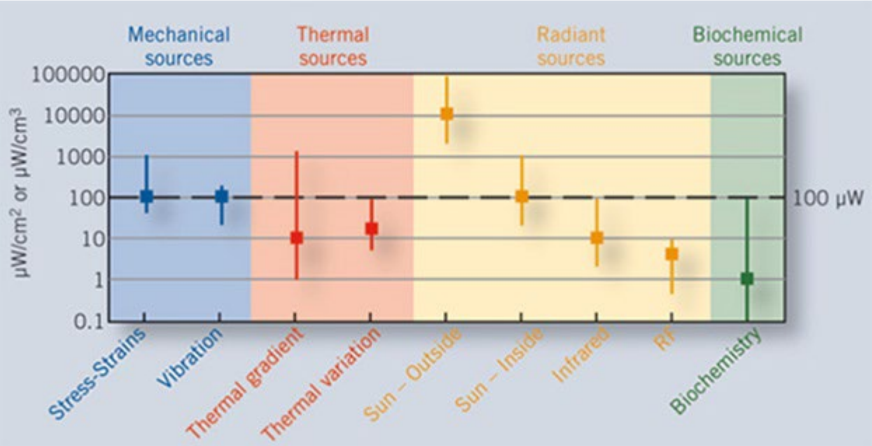


Figure 30: Energy harvesting power compared for various sources

SUN

To understand what direction the PV industry is heading in terms of sustainability and circularity we have to look at current developments that have their origins in the recent history.

Now: made in China

The Chinese take-over of the PV industry starts around 2004, when it begins producing modules mainly with European equipment. With China creating very favourable conditions for the industry to rapidly scale up the Chinese industry could produce panels far below the price of small scale European domestic players. Consequently the European PV industry was basically wiped out around 2012-2014.

Today, Chinese companies have a monopoly position in all major manufacturing steps (see figure 31) with wafer production as an extreme example: 97% of the total global production.
Although the percentage for the cell and module manufacturing may seem lower, it is good to note that the Southeast Asian production capacity volume (the green streams in figure 31) also largely consists of Chinese players seeking to evade US import tariffs placed on Chinese PV panels (IEA, 2023). And even though the EU and US have introduced measures such as import tariffs in the past, the effects on the industry up till now have been relatively minor.

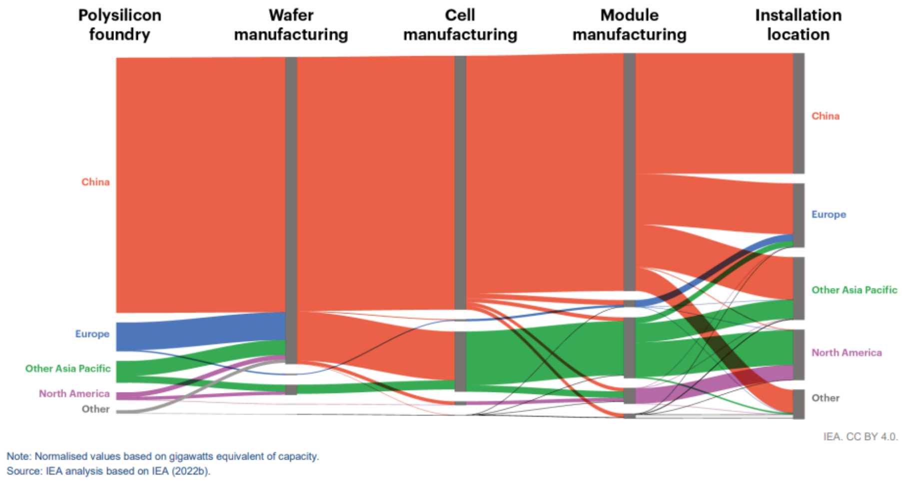


Figure 31: Manufacturing capacity per process step per country

Future: made in Europe?

Three (recent) developments might provide reasons why the time has come for a turning point and for a genuine resurgence of PV panels 'made in Europe' (Jourdan-Huber, 2022),(European Commission, 2022):

1. The expected PV market boom in Europe due to the energy transition leaves room for new (domestic) players to profit from
2. Commercialization of new technological innovations from European research institutions (such as TNO)
3. Renewed interest for European strategic energy autonomy because of supply chain disruptions from China due to COVID-19 restrictions and the consequences of enormous reliance on strategic resources, highlighted by the Russian invasion of Ukraine.

For SODAQ the second point about new technological innovations will be relevant.

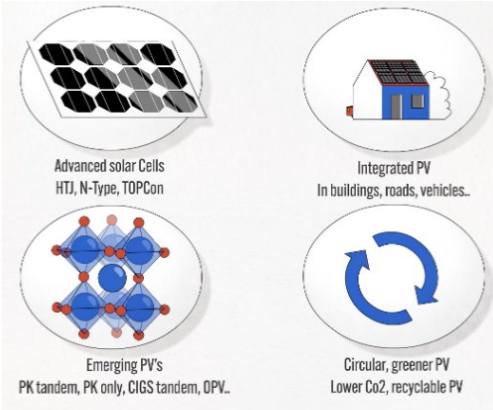


Figure 32: Technological areas of interest for the European PV industry

So what innovation are on the market or currently being commercialized? Four areas of interest have been identified (as shown in figure 32): high efficiency cells, integrated modules (e.g. in products such as vehicles), emerging new PV materials and modules that are more circular and made with a lower CO_2 footprint.
The last area aligns most with the world-friendly vision, therefore this will be discussed first.

Circular PV modules

While First Solar shows that recycling can be profitable (see appendix G1), this is not the case for the standard crystalline-silicon PV modules, such as the current TRACK panel as their design does not allow for efficient liberation of valuable materials (see appendix C).
Several recycling strategies can be used (figure 34), DSM and TNO for example have developed a new, PFAS-free adhesive film, which is designed with an internal 'trigger mechanism' (see figure 33), similar to the reversible adhesion mechanism for recyclable PCB design (chapter 5.2) to liberate the cell and hence the solar grade silicon without contamination (Endurans Solar, 2022).

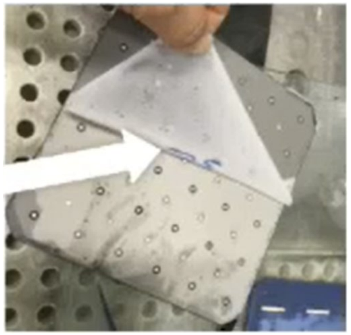


Figure 33: Release encapsulant for a cell, developed by TNO & Endurans Solar

Dutch PV manufacturer Exasun is the first company that announced it is developing a circular monocrystalline-Si panel using this technology (Exasun, 2023). The company is considering introducing a take back scheme based on a deposit-refund model (Solar Magazine, 2020). Another Dutch PV manufacturer, Solarge has recently started mass production of its fully recyclable panels. Solarge claims they are looking at ways to make them out of recycled plastics from 2024 (Lonkhuyzen, 2023), hereby closing the loop for the plastic front and backsheet.
Unfortunately First Solar, Exasun or Solarge do not have solar modules targeted at the IoT market.

Figure 34: Design for recycling and circularity focus areas

Emerging PV technology

The third area of interest from the 'Made in Europe' strategy is the emerging new PV materials that are being developed by European companies and research institutes.
As visible in NRELs efficiency chart (figure 35) the emerging technologies (red) are making steady improvements in terms of their efficiency. However, apart perovskite Si-tandem cells, none has reached the current high plateau of the monocrystalline Si cells (blue) yet. But as many technologies have been invented relatively recently, one can expect that there is still room for innovation. Especially now Europe has set its sights on these technologies to stimulate further commercialization.
A description of the various emerging PV technologies related to IoT products is provided in appendix G..

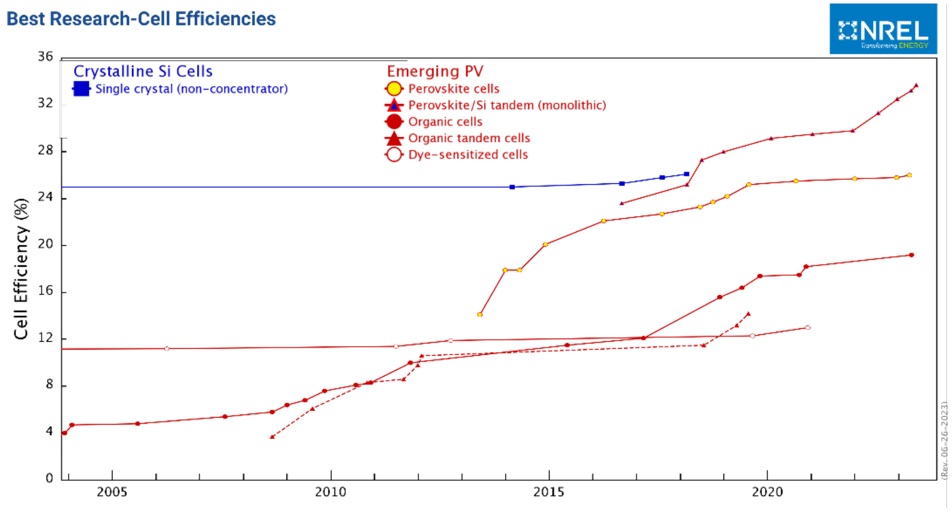


Figure 35: NREL best research-cell efficiencies per PV technology with

Benefits of Emerging PV technology

- Drastically lower CO_2e/kWh than crystalline PV panels 6 (heliatek, 2022) to 10 (Krebs-Moberg, 2020)
- Produced with low-cost, high volume, solution-based roll-to-roll printing techniques
- Few processing steps required
- Processed at low temperatures (100-200 °C)
- Low material usage
- Low-impact materials: non-toxic, extremely abundant naturally occurring and recyclable materials
- Local (European) production
- Lightweight design
- High indoor and shading efficiencies
- Transparency offers possibility for layering different technologies to increase performance, the so-called ‘tandems’
- Multicolour, freeform shape, texturing and flexible substrates: the ability to be applied on a wider variety of applications and new design possibilities

Challenges for Emerging PV technology

- Still relatively low outdoor efficiencies for commercial products (around 9-15% compared to around 20% for silicon)
- Durability: rapid degradation due to humidity, air and UV light. High performance encapsulation with low Water Vapour Transfer Rate and high absorption of UV light is therefore vital.
- Cost: scaling up the production of specialized organic and dye materials makes them more costly at present.
- Recycling strategy

Vehicle-integrated Photovoltaics (VIPV)

The second area of interest are integrated PV panels. This might be relevant not so much for integration into an IoT product, but rather to determine the potential for the logistics sector and hence the future context in which products such as the TRACK will operate.

To date PV systems are already applied on top of distribution trucks of PepsiCo (SUNEW, 2022) and in electric vehicles (Lightyear, Sono Motors). Furthermore a three-years pilot project, SolarMoves, will be conducted in which modelling will be combined with and verified by on-the-road monitoring and testing. Various vehicles (cars, trucks, buses, and vans) will be equipped with integrated solar panels (figure 36). The vehicles will also be equipped with sensors to measure and determine solar irradiation in real-world conditions across Europe (TNO, 2023).

Figure 36: Examples of VIPV vehicle types to be tested in SolarMoves project

Wireless power transfer

To find a way to get rid of the batteries in IoT products wireless power is often cited as a promising direction. Power can be transferred wirelessly through beams of electromagnetic radiation at certain radio frequencies.

Qi wireless charging

An established variant of wireless power transfer is Qi charging. As can be seen from top left rectangle in figure 37, the power rate of Qi charging is high, while the distance to transmitter can only reach a maximum of 4 cm (Wikipedia, 2023). This means Qi wireless charging can be used on top of a charging pad in case the TRACK needs to be recharged.

RF Wireless Power Transfer

Recently a RF wireless power harvesting consortium is set up to work on a common standard: Airfuel (Airfuel, 2023). Currently RF harvesting is mostly applied in factories where sensors need to work autonomously without cables. Also it has started to find its way into the logistics sector.

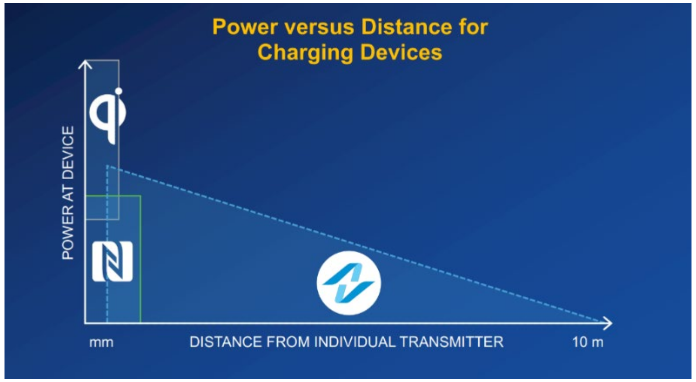


Figure 37: Power vs distance to transmitter per wireless power standard

Figure 38: Williot tracker powered by RF harvesting

For example the Dutch IoT company InnoTractor partnered with WPT supplier Energous and WIlliot to offer supply chain tracking of goods from Sweden to the Netherlands using battery-free postage stamp-sized adhesive tags (figure 38). Data is transmitted using the energy harvested from WPT gateways placed throughout the supply chain (Swedberg, 2023).

RF WPT sustainability

Large downside is the efficiency or rather inefficiency of the transfer: RF WPT is less than 0.1% at a distance of 1 meter (see an example in figure 39). The question then arises how sustainable this method actually is?
For example a study into LCA for the design of battery-less passive infrared sensor for room occupancy tracking with WPT over 5 m shows the 'counterintuitive' conclusion that the environmental impacts over a 10 year lifetime of the product were at least 5.5 to 10.3 higher than the coin cell-powered versions (Gonzales, 2023). The authors therefore underscore the importance of conducting an LCA before implementing such a RF harvesting system.

Block Details	915MHz	2.45GHz	5.8GHz
Tx Conducted Power (W)	1	1	1
DC Power to Storage Element (mW)	**0.853**	**0.119**	**0.021**

Figure 39: Harvesting power compared to input power at 1 m distance

6G Zero energy devices

Using RF harvesting from the mobile network is attractive as it is ubiquitous, as it is always available where there is mobile network coverage. 6G promises a more directed beam to increase RF efficiency (Gupta, 2022). With the level of energy provided by a 6G network a coverage of 20 meters or up to 50 meters without any obstacles could be achieved, but the harvesting energy would still only be around a mW or less (Ericsson, 2023).

Conclusion

- The sun is by far the most powerful source for the harvesting of energy, while RF harvesting is the least powerful source. However WPT can be concentrated at certain points along a supply chain and could this way still provide enough energy for battery-free operation. The main benefit of RF harvesting from mobile networks is that it is almost ubiquitous compared to energy harvesting methods.

- The European solar PV strategy is focused on improving the sustainability aspects of EU made PV panels in order to support the reconstruction of an European industry.

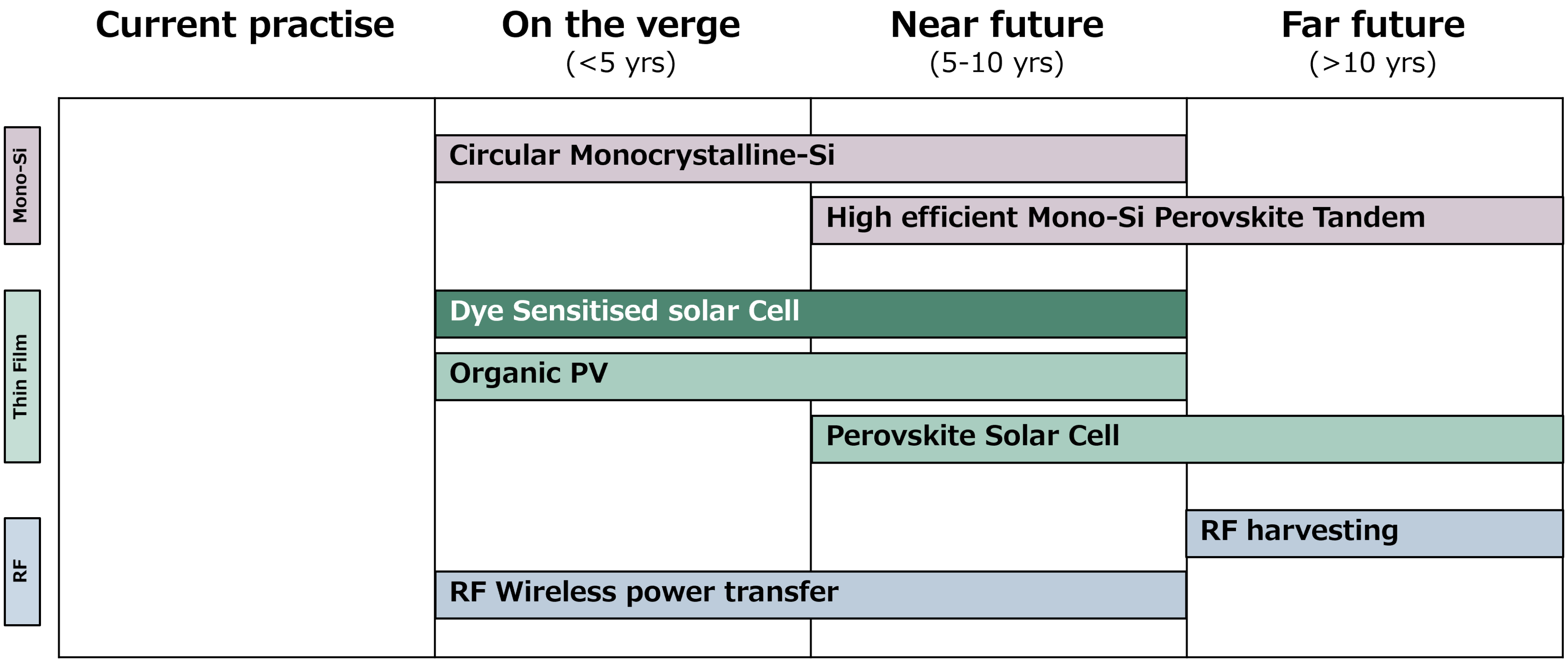
- More circular monocrystalline- Si PV panels are now coming on the market, however they are not yet aimed at the IoT market.

- Emerging PV technologies are aimed at the IoT market and seem to have clear sustainability benefits over mono-Si panels. However efficiency, although improving rapidly, seems to be much lower than TRACKs current PV panel and there are questions regarding durability, cost and a true recycling strategy.

- Solar panels are getting more and more integrated into assets in the logistics sector, starting off with vehicles such as trucks and vans.

- The sustainability improvements of WPT are questionable and should be looked at carefully using a LCA.

Energy harvesting technology roadmap



5.4 Enclosure materials

Although the electronics are the main contributor to the footprint finding a more world-friendly material for the enclosure, it is still considered a key priority by SODAQ and something that might be relatively easy to achieve. Currently the TRACK is made from a virgin ABS-PC plastic and the question will be what material alternatives with lower footprint are currently available or are about to become available on the market.

Recycled plastic

Using recycled content instead of virgin material is often considered to be the 'low hanging fruit' for impact reduction of a plastic product enclosure. However the term 'recycled content' can mean a lot of different things so it is good to state more specifically what kinds of recycled grades there are and which of them can be considered the most circular option.

Plastic degradation

The issue with recycled plastic is generally their low quality. The consequence of applying degraded plastic is that the product will become more brittle and thus has a lower elongation at break and a reduced impact resistance. The quality of a recycled grade can be tested using a Drop-in Method (PolyCE, 2021). If the quality is insufficient, the degradation in mechanical properties can be compensated for by applying additives such as thermal stabilizers, UV absorbers, impact modifiers (e.g. glass fibres) and pigments and by compounding (i.e. adding a virgin material fraction).

However plastics do not only degrade during recycling, but have already degraded after a first production run. The various causes for degradation are listed in figure 40.

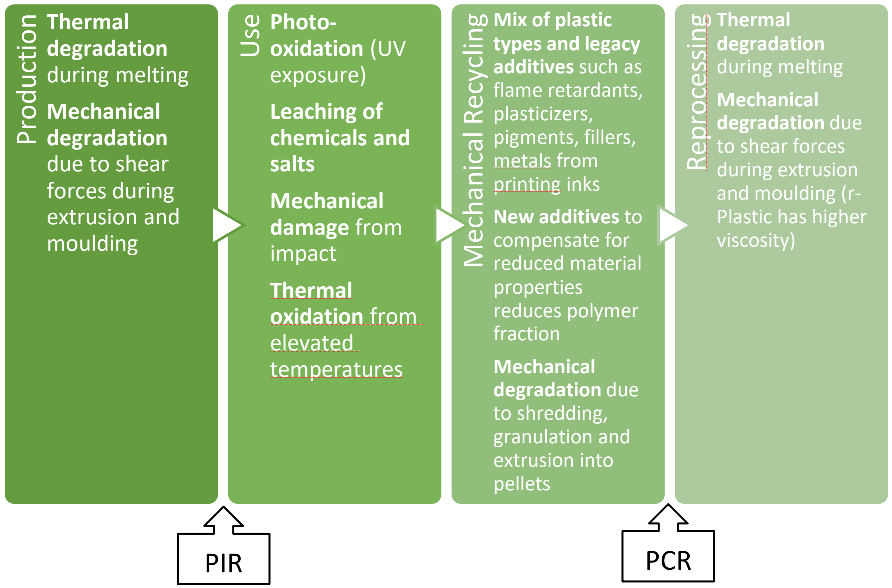


Figure 40: Plastic degradation for each phase of the TRACK lifecycle

Post-consumer vs. Post-Industrial recycled content

First there is an important distinction between Post-Consumer Recycled plastics (PCR) and Post-Industrial Recycled plastics (PIR). PCR has been made from plastics that actually have been used in a product, while PIR is made from production waste. PCR grade plastic has lower and sometimes significantly lower mechanical properties, whereas PIR recyclate has mechanical properties that come close to that of the virgin material but has been degraded slightly due to thermal and mechanical stresses during the production run.

It is often unclear which of those two types has been used in a product with recycled content. However due to the superior mechanical properties of PIR, it is often a more attractive option for companies to transition to. The consequence of using PIR will be that the market for PCR plastic will not be able to develop as there is less incentive for recyclers to process WEEE plastics at higher quality. Furthermore production waste should be minimized anyway and therefore PIR plastic should not be stimulated. That is why making a world-friendly enclosure means choosing for a PCR instead of PIR plastic.

Plastic recycling hierarchy

For PCR plastics the following recycling hierarchy is defined (adapted from Schwarz, 2021). The hierarchy is based on the degree to which the polymer stays intact. The lower the amount of processing necessary for each step, the smaller the loop (in figure 41) and generally the lower the environmental impact.

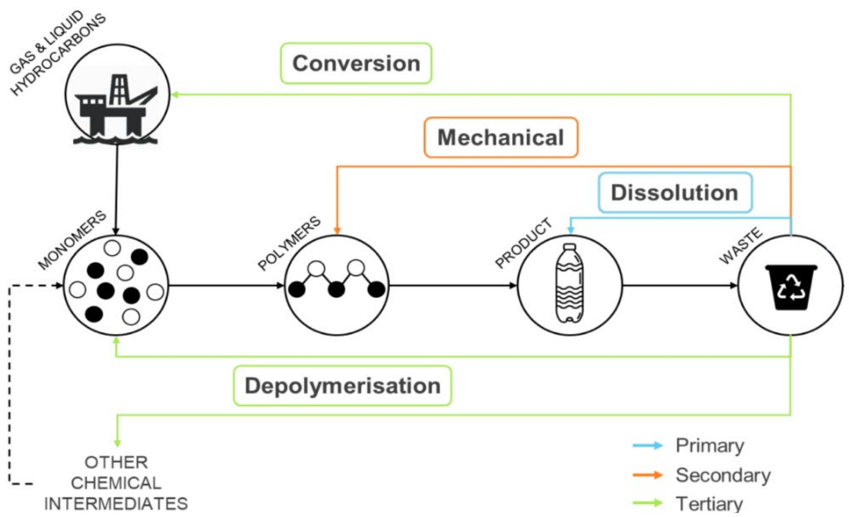


Figure 41: Overview of recycling strategies

1. **Primary recycling or closed-loop recycling**
   In primary recycling the input material is recycled to make products with the same properties as the original product over and over again. This means that the material will be able to remain in the (closed) loop.

   Primary recycling options are:
   1.1. Closed-loop mechanical recycling
   1.2. Dissolution purification

2. **Secondary recycling or open-loop recycling**
   In secondary recycling the input material is recycled but in each loop the quality degrades to a level where the plastic can only be applied in other, usually lower value products until the quality becomes so low that this is no longer a viable option (i.e. the material falls out of the loop and therefore the loop is considered open). Currently, the majority of WEEE plastic that is recycled is processed this way.

   Secondary recycling options are:
   2.1. Open-loop mechanical recycling

3. **Tertiary recycling or chemical recycling**
   In tertiary recycling the input material is recycled by reconstructing the plastic polymer. This can be done either by bringing it back to the monomer level directly or by converting the plastic into a (syn)gas or naphtha (oil) first, from which the monomer can then be derived through feedstock refinement and cracking.
   Given that the plastic polymer is reconstructed using the same monomers as the original polymer, the 'recycled' polymer generally has mechanical properties equivalent to its virgin counterpart.

   Tertiary recycling options are:
   3.1. Thermochemical recycling
   3.2. Depolymerisation

Plastic recycling performance comparison

In figure 42 the various recycling technologies are put side by side based on the purity of the polymer that can be achieved after recycling. In the figure it is clearly visible that depolymerization has the potential to keep the material in the same loop over countless material life cycles. Furthermore closed-loop dissolution purification will be able to create a near virgin recyclate, hereby slowing down the inevitable downcycling of the plastic most effectively, while leaving the plastic intact.

>> More specific advantages and challenges of the different strategies and biobased plastics and potential future opportunities for the TRACK are highlighted in appendix H1.

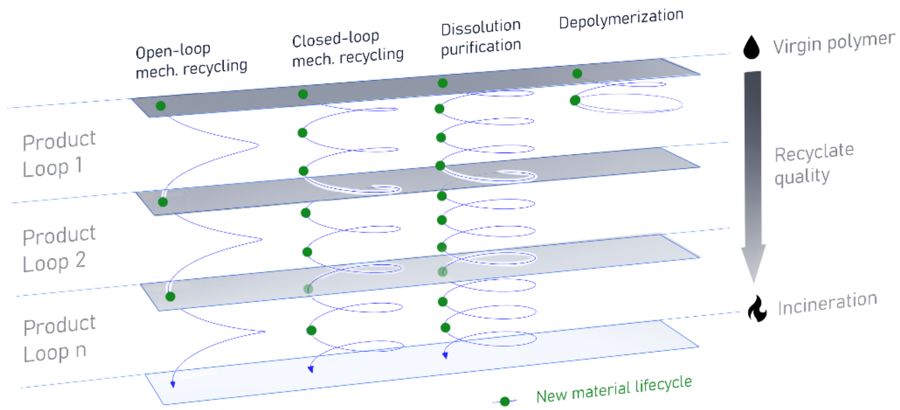


Figure 42: Illustration of PCR plastic quality over material lifecycles per recycling strategy

Biobased plastic

A renewable alternative to recycled plastics are biobased plastics, derived from plants, bacteria, fungi or algae biomass. Plants remove CO_2 from the atmosphere as they grow and store the carbon in the form of biomass, which is consequently stored in the biobased material until it gets incinerated. Biobased plastics are, when all indirect emissions are ignored, therefore also considered carbon-neutral over their life.

Biobased plastic hierarchy

An important distinction that needs to be made concerns the source of the biomass material. The hierarchy for the sourcing is based on the generations of biobased plastics (adapted from Lambert, 2017). In this case the last generation is preferred over the first generation as it tries to solve the issues that arise from the previous generation(s).

1. **First generation**
   Biobased plastic is derived from carbohydrate biomass from edible crops (e.g. starch and cellulose from corn)
2. **Second generation**
   Biobased plastic is derived from non-edible waste materials (e.g. agricultural waste)
3. **Third generation**
   Biobased plastic is derived from algae and seaweed biomass to improve production yield

Drop-in variants

Biobased drop-in variants of commonly applied plastics have identical chemical composition to their fossil-based counterparts. This means they can be recycled together with standard WEEE plastics of the same type and they can be used as compounding material for recycled plastics without creating a blend, enabling easy separation and hence recycling at EoL.

Evaluation

To provide a recommendation about what materials could have a lower environmental impact while still being able to meet the requirements (e.g. smooth, defect free surface quality suitable for reliable sealing) of the TRACK product line, the gathered options need to be evaluated.

Enclosure material selection criteria

Based on the goal of a world-friendly TRACK (Section 2.6), the literature research documented in appendix H1 and H2, the following list of wishes is composed.

	ENCLOSURE MATERIAL WISH LIST
1	The cradle-to-gate footprint is significantly lower than virgin ABS-PC
2	No new fossil fuels extracted (directly) as raw material
3	Production and recycling are done using renewable sources
4	The material can be kept in the same product loop for multiple material lifecycles, hereby avoiding production of new material and lowering emissions over time through postponing moment of incineration
5	The material is a second or third generation biobased plastic
6	The material can be sourced and processed locally (within the EU) to lower emissions from transport
7	The material has the potential to be (re)processed in small material volumes (< 600 kg/year) cost-effectively
8	Material expression can be used for marketing of a 'world-friendly' product

Material selection

From desk research and by using the handy preselection from the positive plastic kits (Positive Plastics, 2022), a list with potential opportunities for the next generation TRACK is formed. A summary of the most important advantages and disadvantages is put into the table. Based on the most important advantage or showstopper, highlighted in the table by putting it in bold, a selection is made for each material.

MATERIAL SOURCE	MATERIAL TYPE	ADVANTAGES	DISADVANTAGES	
CLOSED-LOOP MECHANICAL RECYCLING	PC+ABS Eco (MOCOM & WIPAG RaaS, DE)	Fully optimized mechanical recycling process is very efficient while retaining a relatively high quality recyclate (see figure 42)	**SODAQ likely cannot provide material in large enough volumes** to make this a profitable recycling method	
CLOSED-LOOP DISSOLUTION PURIFICATION	ABS (Recycling Avenue, NL)	Quality degradation per loop is relatively low and **recyclate can be of near virgin quality** (see figure 42) keeping the material in the loop for a long time No restricted substances in recyclate	Maturity of the technology might mean low yield, limited material supply and high costs	✓
OPEN-LOOP MECHANICAL RECYCLING	ABS (Coolrec, NL)	Mechanically recycled ABS (Moulded mixed polymer in figure 43) has a relatively low footprint Following the recycling guidelines is the only adjustment required Economies of scale and wide availability makes it the most competitively priced type of recyclate	**Recycled quality is the lowest of all recycled plastic types and therefore cannot be reused for the same product loop** (see figure 42). This could mean that surface quality is too low for reliable sealing over a complete production batch or that the material is too degraded to retain the IP rating over the projected lifetime High chance of restricted substance concentrations in they recyclate	

DEPOLYMERIZATION	DuraPET from rPET (CuRe, NL), (Ioniqa, NL), (Carbios, FR)	The material **can theoretically be recycled ad infinitum** (see figure 42) Almost 60% lower environmental footprint per kg (Carbios, see figure 43)	DuraPET has lower mechanical properties than ABS-PC (nearly 25% lower modulus) so more material will be needed (see figure 44)	✓
BIOBASED PLASTICS	Makrolon RE drop-in replacement for PC with 72% biobased content (Covestro, DE)	Second generation biobased Extremely low impact (nearly 85% lower than virgin ABS-PC) through to use of renewable energy (see figure 43) Transparent housing option	**Significant fossil based virgin plastic fraction**	
	PEF (Avantium, NL)	Better mechanical properties than standard PET Can be recycled together with PET	**First generation biobased** Relatively high environmental footprint	
	Primeflex carbon-negative biocomposite (Made of Air, DE)	**Carbon-negative!** Can be exploited for marketing purposes Second generation biobased	Leaves some fundamental questions about EoL strategy open Much lower mechanical properties than current material (35% lower modulus, see figure 44), however counterintuitively more material might not necessarily be a bad thing with this type of material Wall thickness requirement of at least 1 mm might make detailing challenging	✓

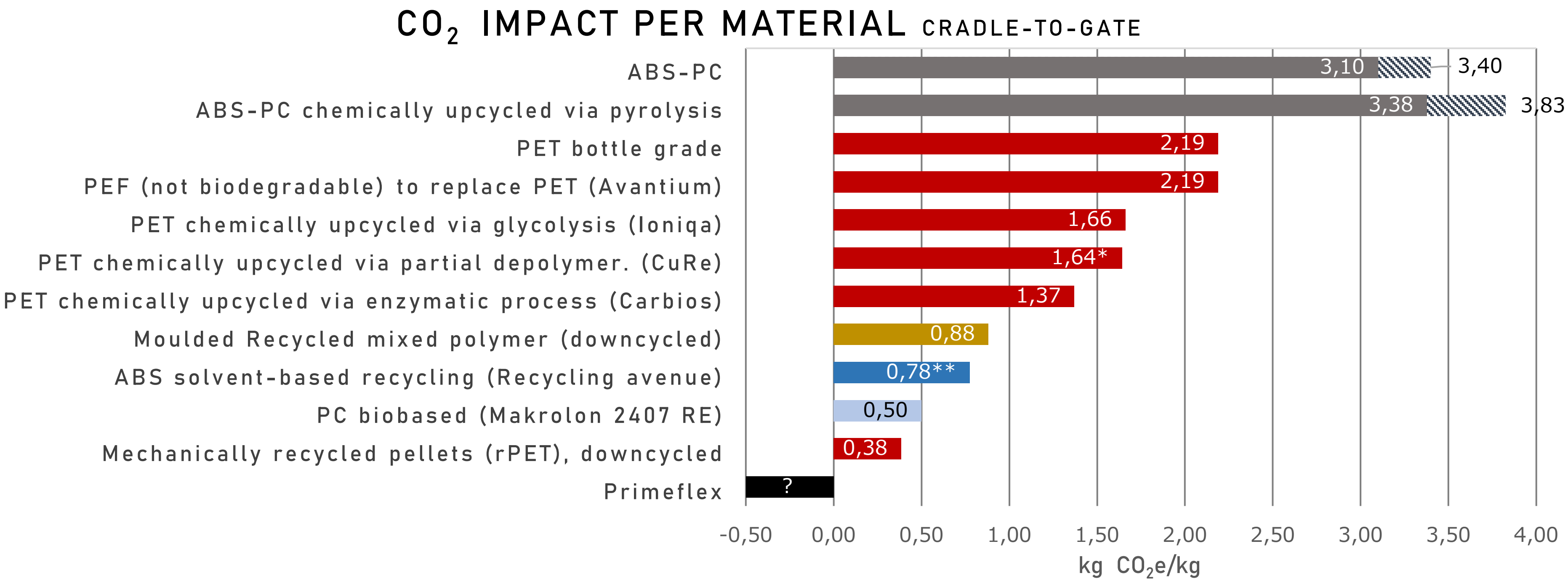


*Figure 43: Environmental footprint of material options (based on data from the IDEmat 2023 database or manufacturer data) * 25% less than virgin PET ** 75% less than virgin ABS*

Material preferences

So the following materials meet most wishes without showstopping disadvantages and should be investigated further (in number of preference):

1. **Primeflex** carbon-negative material reverses emissions instead of simply lowering them
2. Infinitely looping PET avoids new (fossil-based) plastics and grafted PET (**DuraPET**) might become a fully circular plastic for electronics
3. Near virgin quality ABS **(Recycling Avenue)** slows down the need for new (fossil-based) plastics more effectively than mechanical recycling method using a relatively low impact recycling method aimed at WEEE plastic.

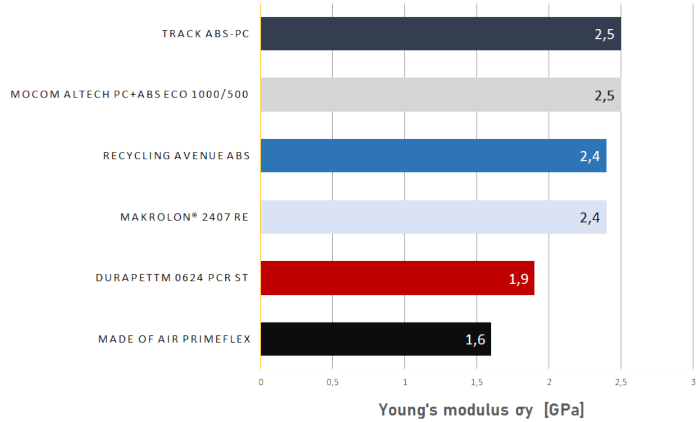


Figure 44: Yield strength of material options

Material application research

Made of Air Primeflex

The material sample obtained from the Positive Plastics kit (45a)showed the potential of the material for the TRACK as it has sufficient surface quality, tolerances below 0.2 mm and no noticeable warpage so that reliable sealing should be possible. The question whether the yield strength will be sufficient for the final product to survive a drop test is still very hard to answer based on the sample alone.

Made of Air was contacted with a request for further information and the possibility to test the material in one of SODAQs existing moulds.
Unfortunately the company refused to respond to the request.

Currently no examples of injection moulded (electronic) products are available and the company states that it is working with companies to bring the first products with the material to the market in the coming years. This means that the material is still very much under development and likely won't become available for smaller players like SODAQ in the near future.

Figure 45: (a) Positive Plastics Primeflex material sample (b) SODAQ Air

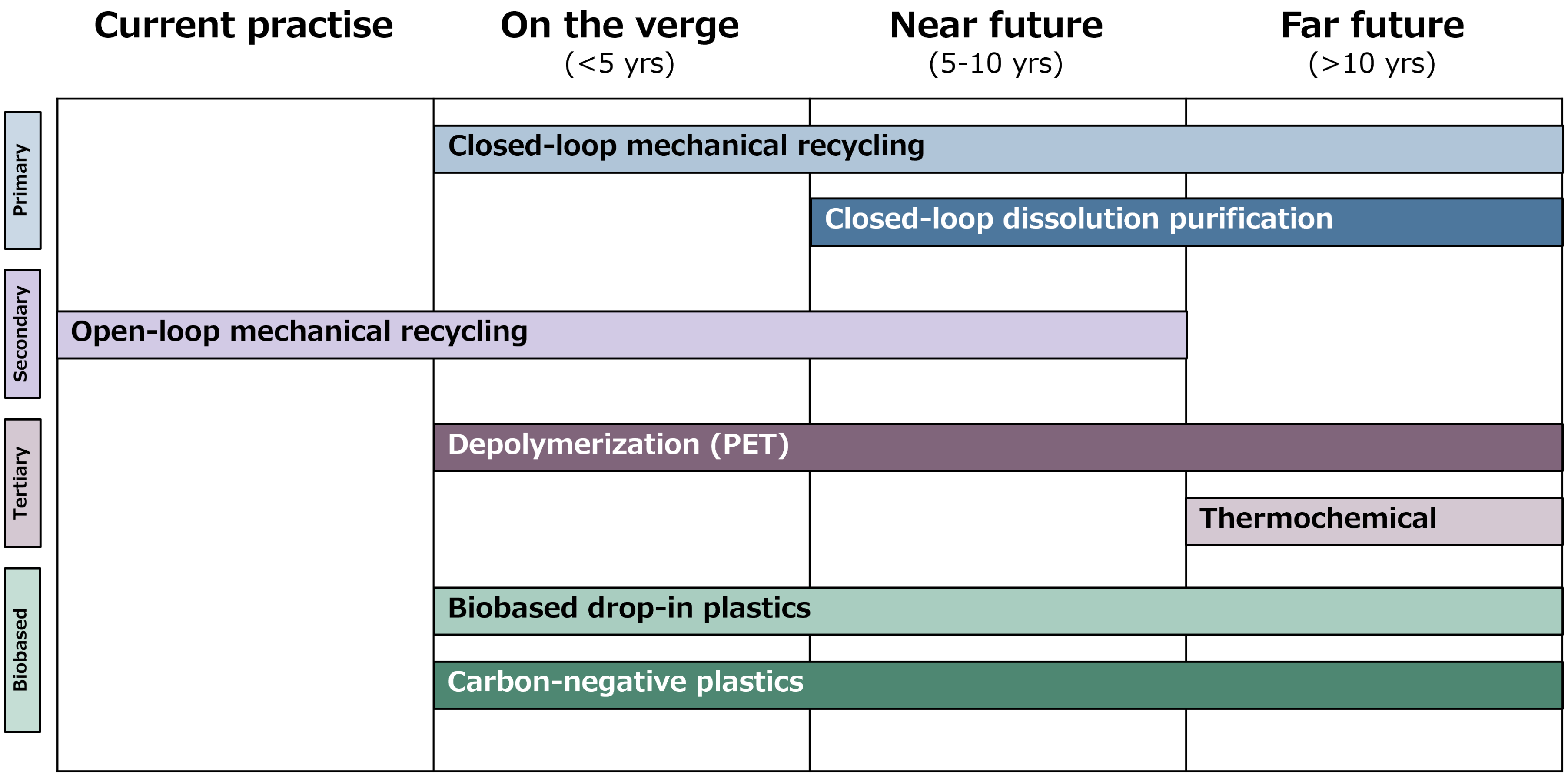
Polyvisions DuraPET PCR

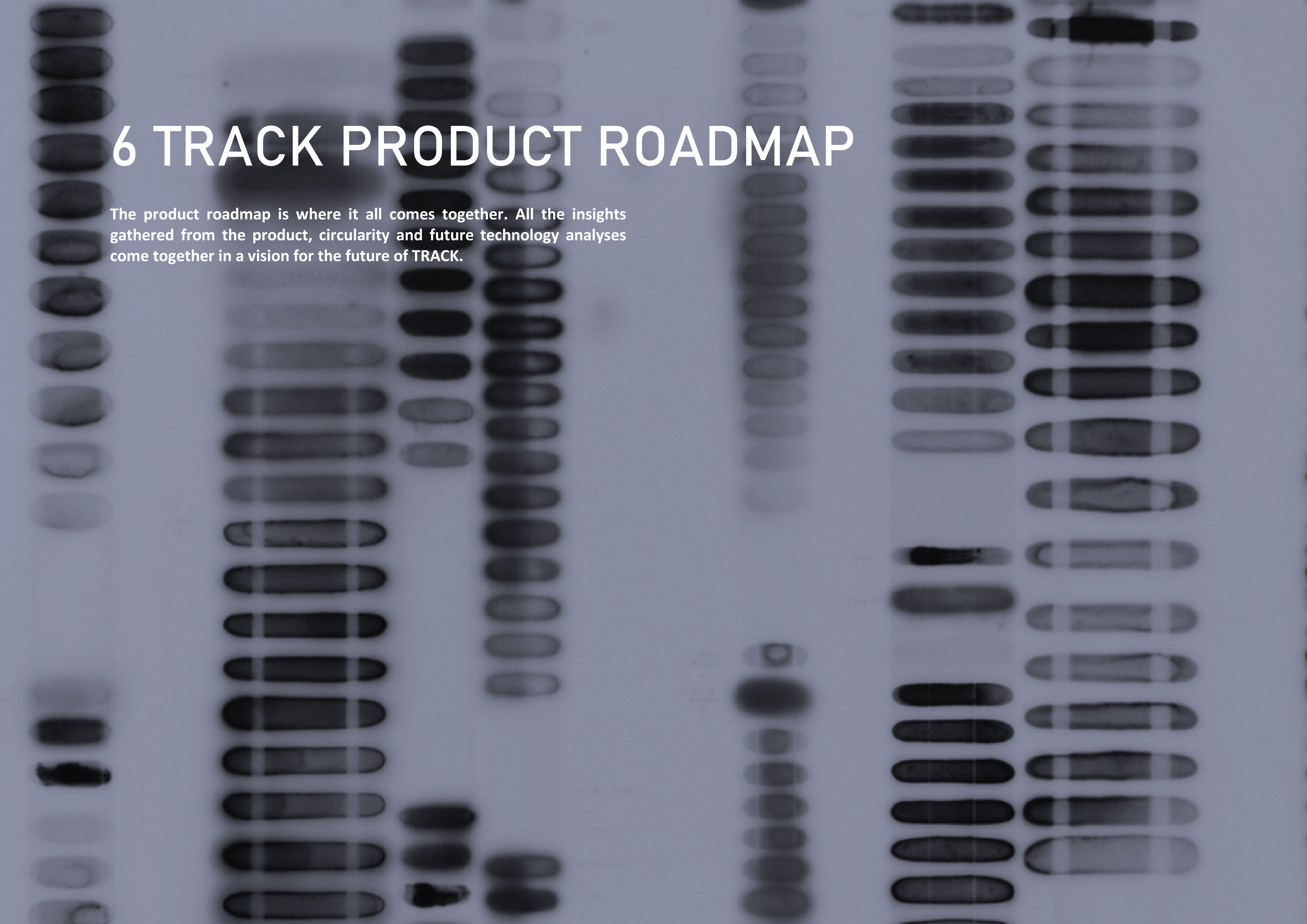
Reaching out to the company Polyvisions was more successful and the material engineer of the company was positive that DuraPET PCR could fulfil the requirements of the TRACK.
The idea was to perform tests with the material using the mould of the SODAQ Air enclosure, depicted in figure 45b. Unfortunately the efforts quickly stranded due to fact that SODAQs Chinese injection moulding partner did not have the right drying equipment to meet the extreme requirements of the DuraPET material. The moisture level cannot be higher than 0.02% before injection moulding. Higher levels would impact physical properties of the product and brittleness will occur. To achieve such a low moisture level a dessicant bed dryer is required (appendix H3).
A request was sent to look for a company in the area that would have the right equipment to process the material. The contact person from the company replied that she contacted every injection moulding company in Shenzhen region, but apparently none of them had a dessicant bed dryer. Sending the material predried would also not be an option according to Polyvisions as it would not be possible to retain the moisture level during transport.

Recycling Avenue ABS

The material quality of ABS after dissolution purification recycling is near virgin so it is safe to assume the quality of the material will not be the main issue, but rather the state of the technology. When will the process be ready for mass production? To this end an interview with one of the founders of the Recycling Avenue was arranged.
The main conclusion from the interview (which can be found in appendix H4) is that the maturity of the technology is still years away. However interestingly the small volumes that can be processed in the pilot plant would be a very good match with relatively low material demand for the TRACK line and therefore the product could even become a showcase for the Recycling Avenues material quality.

Roadmap enclosure materials





6 TRACK PRODUCT ROADMAP

The product roadmap is where it all comes together. All the insights gathered from the product, circularity and future technology analyses come together in a vision for the future of TRACK.

6.1 TRACK future vision

Future network technologies form the basis
From the standpoint of SODAQ, being an early adopter, the assumption is made that new network technologies introductions will form the basis for future TRACK versions in the product roadmap. New communication and location technologies provide the opportunity of bringing down the number of IC components, reducing the energy consumption, increasing energy harvesting potential or offering a more reliable tracking service through worldwide network coverage.

Circularity roll-out strategy
Design for maintenance and recycling are seen as the most relevant circular strategies by SODAQ and should therefore be the main aim for the first iteration of the TRACK. The product roadmap shows which circular strategies further can be introduced with what version.

Design for backward compatibility
While SODAQ does not (yet) see the potential for an upgrade strategy, reuse was identified as a viable circular strategy. However to make sure that TRACKs can actually be reused after 7 years in the field, it is still relevant to look into cost-effective ways to upgrade the network component as network end-of-support prevent reuse.
An upgrade strategy does not only require the new version to be ready for the next version, forwards compatibility, it is also requires a future version to be backwards compatible (for certain components).

Forward compatibility (upgrading)
Upgrading the TRACK with new electronic components is only feasible if future components fit in the existing enclosure. To bring the cost of component replacement or spare parts down, standardization of components or sharing component architecture between a current and a future generation can be a solution. This way components can be ordered more frequently and in higher volumes. It also means that the roadmap shows an enclosure design that has to stay consistent or even identical for at least two successive generations.

Integration of lower impact components & materials
The roadmap shows the integration of the particular more world-friendly components (from chapter 5) that were considered to be ready for adoption in the TRACK at a certain moment in time.

Asset integration
Given the rise of the circular and the role of more service-oriented business models, the demand for ‘intelligent assets’ will likely continue to grow in the future. As figure 46 shows, not only location, but also condition (sensors on the asset) and availability (intelligent software service at cloud backend or edge AI) will more and more become drivers of a broader asset tracking ecosystem (Ellen MacArthur Foundation, 2016).

Co-development

Working with existing customers unlocks better integration of a TRACK (and sensors) into the assets. Integration will lead to less chances of the TRACK getting damaged and opens up new business opportunities for closed loop operations and asset sharing as explained in section 3.6.
Also the co-development makes it possible to discuss the EoL strategy and the accompanying mounting design can be discussed already this way.

Automation in logistics

The trend of ever increasing automation in the logistics sector is expected to continue (DHL, 2022) and a more automated supply chain will likely result in the discontinuation of the TRACK Active variant with a manual button. The TRACK Active is therefore no longer included in the roadmap.

	INTELLIGENT ASSET VALUE DRIVERS		
CIRCULAR ECONOMY VALUE DRIVERS	Knowledge of the **location** of the asset	Knowledge of the **condition** of the asset	Knowledge of the **availability** of the asset
Extending the use cycle length of an asset	• Guided replacement service of broken component to extend asset use cycle • Optimised route planning to avoid vehicle wear	• Predictive maintenance and replacement of failing components prior to asset failure • Changed use patterns to minimise wear	• Improved product design from granular usage information • Optimised sizing, supply, and maintenance in energy systems from detailed use patterns
Increasing **utilisation** of an asset or resource	• Route planning to reduce driving time and improve utilisation rate • Swift localisation of shared assets	• Minimised downtime through to predictive maintenance • Precise use of input factors (e.g. fertiliser & pesticide) in agriculture	• Automated connection of available, shared asset with next user • Transparency of available space (e.g. parking) to reduce waste (e.g. congestion)
Looping/ cascading an asset through additional use cycles	• Enhanced reverse logistics planning • Automated localisation of durable goods and materials on secondary markets	• Predictive and effective remanufacturing • Accurate asset valuation by comparison with other assets • Accurate decision-making for future loops (e.g. reman vs. recycle)	• Improved recovery and reuse / repurposing of assets that are no longer in use • Digital marketplace for locally supplied secondary materials
Regeneration of natural capital	• Automated distribution system of biological nutrients • Automated location tracking of natural capital, such as fish stocks or endangered animals	• Immediate identification of signs of land degradation • Automated condition assessment, such as fish shoal size, forest productivity, or coral reef health	

Figure 46: Intelligent assets value drivers in a circular economy
(Ellen MacArthur Foundation, 2016*)*

6.2 Track future positioning

Stealth vs. TRACK product lines

The STEALTH product is a lightweight version of the TRACK and might be regarded as the next evolution in the TRACK line. Although both products have some overlap in their functionality, SODAQ believes that the TRACK will have added value in the future as the STEALTH still has limitations due to its compact size.

Also some technological developments from chapter 4 might be more relevant for the more simple STEALTH. That is why the choice has been made to include potential iterations of STEALTH (which is currently still in the piloting phase) into the roadmap for the TRACK as well.

STEALTH

Minimalistic tracker for low value assets
in closed-loop supply chains

Location tracking

- Works infrequently (when there is LTE coverage)
- Limited amount of messages

Swappable

- Small supercapacitor
- Chargeable after asset returns
- Thin, flexible enclosure

TRACK Core

Multirole tracking solution for high value assets
in closed loop supply chains

Location tracking

- Works practically anywhere
- High position accuracy
- Frequent message intervals

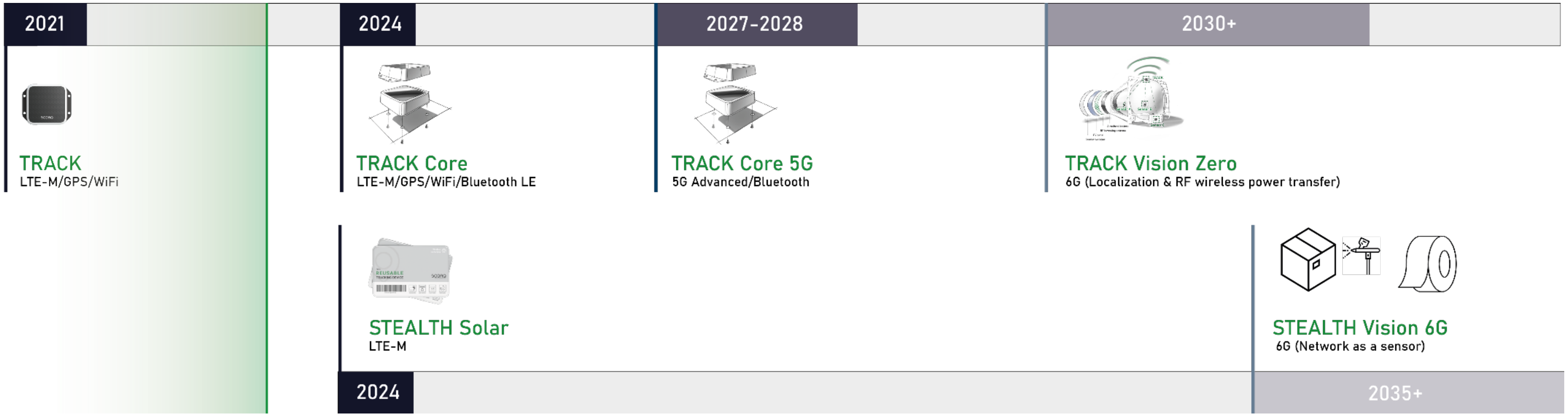
Condition monitoring

- Hub for transmitting sensor data about asset or its contents.
- Higher processing power and energy budget allows for simple initial sensor data processing

Integrated solution

- TRACK and sensors will become a fundamental part of the asset
- Independent operation for 7 years outdoors
- Durable and impact resistant enclosure

6.3 Product roadmap



Stealth Solar 2024

Given that the stealth has less features and hence a simpler circuit architecture, it would be much easier to implement a FHE design instead of a traditional FR-4 or a flexPCB based design. From the development process of the STEALTH, SODAQ can get familiar with the specific requirements of the technology and connect with hardware partners before starting development of a more complex FHE circuit design for the TRACK Core 5G. Also the ultra low power requirements and flexible nature seem to be a good fit for emerging PV panels.

Stealth 6G Vision 2035+

6G sensing will make the STEALTH transition from an active location transmitter to becoming a passive piece of hardware.
The shape it will take is hard to define at this stage of the technology, but it is not unimaginable that it might come in some form of a reusable RFID-like sticker/tape which can be used similarly to the current Williot sticker but without the need for a dedicated infrastructure.
Or it might come as a special (recyclable/biodegradable) coating layer on the asset that creates a uniquely patterned surface that can be sensed and identified by the 6G network equipment or as a Reconfigurable Intelligent Surface (see appendix E)

TRACK Core 2024

Product focus

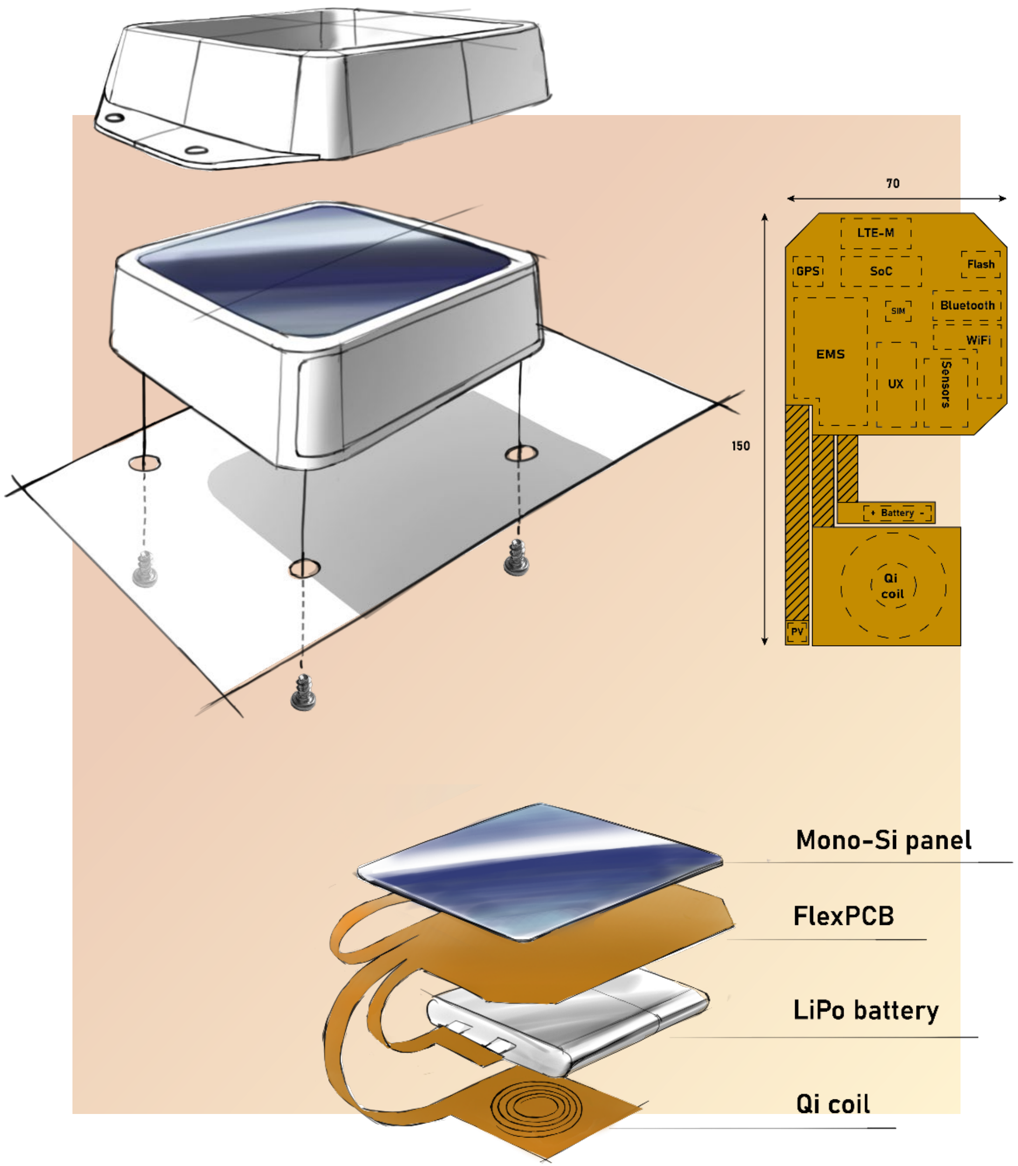
- Kick-off of world-friendly product design with a enclosure of low impact material (e.g. Recycling Avenue ABS)
- Design for asset integration (TRACK Core with customized mounting bracket)

Circularity focus

- Design for reuse
- Design for maintenance (exchange battery & PV panel)
- Possibility to upgrade PCBA (exchange PCBA)
- Closed-loop recycling of enclosure material
- Create framework for product passport and investigate options for securely sharing material information with relevant stakeholders (e.g. blockchain technology)
- Business model for maintenance & recycling

Redesign

- Forward compatible housing (for next-gen Core 5G PCBA)
- PI Flex PCB + Bluetooth LE component for sensor connectivity
- Qi wireless charging (instead of USB) reduces the number of openings and hence water intrusion pathways
- Disassembly of all components from enclosure (for recycling)
- 3D printed mounting bracket (e.g using generative design)



TRACK Core 5G 2027-2028

Product focus

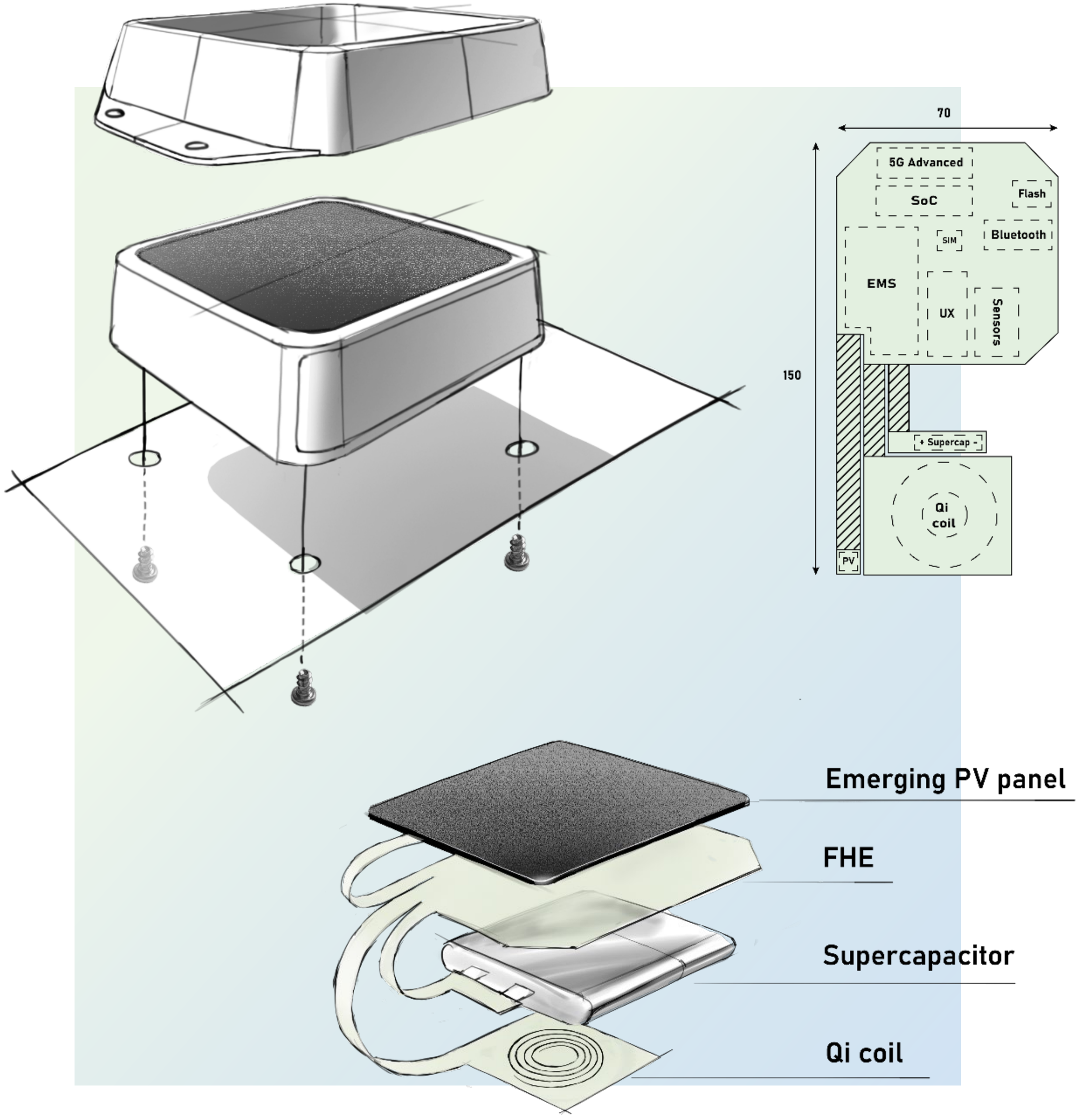
- Modular PCBA
- CO_2 negative housing (Primeflex)
- More world-friendly electronic components
- Expand asset integration options
- Update product passport and pilot with limited components such as the battery
- Enclosure is back-ward compatible with Core 2024 version

Circularity focus

- Repair & upgrading of PCBA
- Upgrading to 6G & RF harvesting
- Business model for upgrading PCB components

Redesign

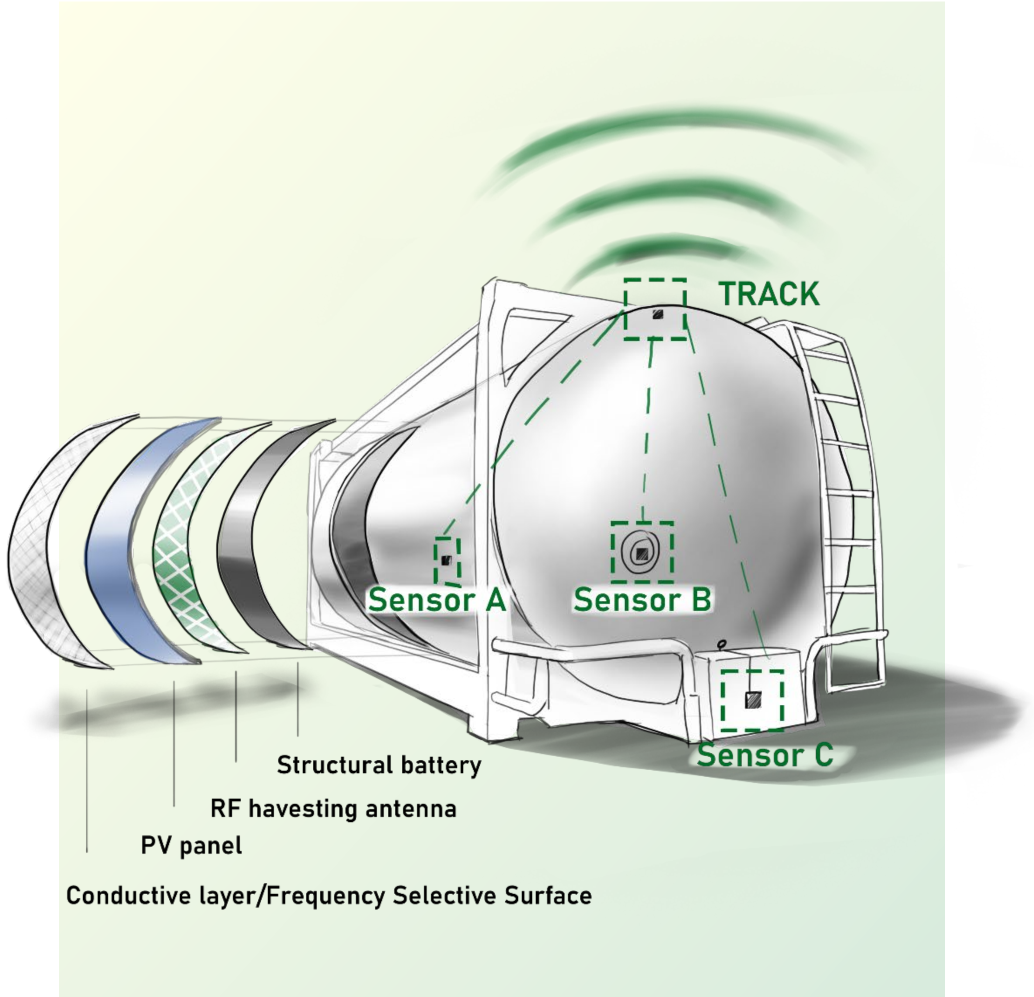
- Additive PCBA manufacturing (FHE) with (depolymerization) recycled PET substrate, reversible adhesive and mounted using a lower power soldering alternative
- Maintain existing enclosure dimensions with Primeflex material
- Integration of flexible emerging PV panels
- Integration Supercapacitor or (semi) solid state battery with longer life-time (more cycles) and lower environmental impact (recycled) materials



TRACK Vision Zero 2030+

Product focus

- Asset co-development can benefit the impact of the TRACK itself as structural parts can take over functions from the TRACK.
- Asset structural parts take over power functions by for example:
    - RF harvesting layer
    - Integrated PV panel layer
    - Structural battery layer
    - Conductive layer
- Asset structural parts take over antenna and ground plane components
- Outer protective layer with conductive traces should be easily removed to change the frequency or can be reprogrammed
- TRACK can become just an integrated chip with an e-SIM that can be plugged into the conductive layer for power and antenna connection
- Battery-free sensors can also be plugged into the conductive layer



Circularity focus

- Business model for sharing service of intelligent assets

Redesign

- Complete rethink of an asset. SODAQ develops a layer structure for the assets that work with their printed TRACK SoC

6.4 Concept discussion

The roadmap with the individual concepts is discussed within the industrial design team and the new communication and location technologies are discussed with the antenna and hardware engineers. During the discussion the value of the concept for SODAQ is determined and in particular the viability of the network technologies is discussed.

STEALTH 6G Vision

Value for SODAQ

SODAQ considers the STEALTH not part of the current assignment however the 6G sensing aspect can be a very interesting aspect to keep an eye on. However considering the slightly sceptical view on the promises about new network technologies SODAQ does not expect it will be able to do anything useful with this information in the near future.

Privacy concerns of 6G sensing

Previously only active devices have been able to be tracked but now 6G sensing may enable tracking and potentially identification of anything in the environment, including humans that do not carry an active device. This has implications for privacy and SODAQ expects this to slow down adoption, also given initial resistance towards 5G from parts of society.

TRACK Core

Value for SODAQ

From a business perspective SODAQ is most interested in the next iteration of the product line that it could bring to the market. Therefore working out this version will have a value for SODAQ. The main focus should be the enclosure out of recycled plastic. However the innovative character of the resulting concept is expected to be relatively low compared to the other concepts.

FlexPCB

SODAQ has its reservations about using a flexPCB as it needs to be secured properly to the enclosure somehow to prevent the components such as the accelerometer from vibrating, giving wrong readings.

IP rating

SODAQ would like to get the IP rating tested before approval of the concept.

TRACK Core 5G

Value for SODAQ

Compared to the first TRACK Core version, working out its proposed 5G successor might have more value for SODAQ as this version will act more as an inspirational concept where some ideas that might not be fully realistic can be worked out. It also helps in seeing how the first Core version should prepare for its successor and most aspects of the enclosure design will be shared with the first version of Core anyway.

Limitation of 5G Advanced

SODAQ expects that 5G Advanced could be the next step for the TRACK on the long term. However they do not know if 5G will be able to match the accuracy of GPS in rural areas as promised, so GPS would still be required. SODAQ also remains sceptical as 5G has been hyped up in the past, but those promises never seemed to materialize, at least for the IoT part of 5G.

Circular business model

SODAQ is interested in how the implementation of the proposed circular strategies could look like in practise, as currently it is difficult to imagine (especially for upgrading) what would be needed to make it work.

TRACK Vision Zero

Value for SODAQ

According to SODAQ the TRACK Vision Zero contains interesting aspects, but is considered too much in the future with a lot of open questions. For example the concept is very dependent on the cooperation/integration opportunities SODAQ is able to secure over time. The asset business is very conservative as there are lots of safety aspects to take into account. The value for SODAQ would therefore be low at the moment.

Limitation of 6G

The higher the frequency of the radio wave, the lower its range. 6G cell towers are expected to have a range up to only tens of meters, whereas for LTE-M (part of 4G) towers this can be several kilometres (see figure 47). The practical implications of achieving full coverage in cities would mean that at every street corner a 6G cell tower needs to be placed. SODAQ therefore expects this to take a many years. Furthermore SODAQ expects that 6G will only make sense in dense urban areas where a lot of users (humans or IoT devices) that can benefit from the low latency and high bandwidth improvements.

Opportunities of 6G

The higher the frequency the lower the required ground plane length (see appendix A3), this means that 6G devices could indeed get a lot smaller in the future if no other frequencies need to be used.

Circularity of the asset

By full integration of the TRACK into the asset and by integrating electrical components in the asset itself, now the circularity of the asset also needs to be taken into account. As this is beyond SODAQs control this might make the system less world-friendly rather then improving it.

Concept choice

In the end the choice was made to continue with the development of the **TRACK Core 5G** as it is expected to bring the most value for SODAQ. SODAQ is interested in the embodiment of this concept and integration of the components.

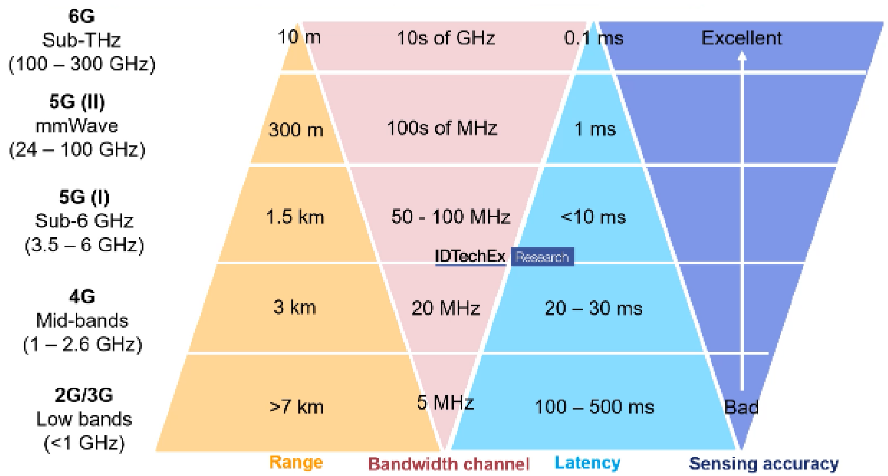


Figure 47: Typical performance per network standard

7 TRACK CORE 5G EMBODIMENT

With the choice for the Core 5G concept, the ideation phase can start. In this phase the TRACK is redesigned based on the aims of the concept and the redesign goals of chapter 4.

New goals

- Reduce the battery replacement time significantly
- Enable disassembly of the PV panel
- Integration of a modular, flexible PCBA
- Provide the option to integrate (more flexible) emerging PV panels
- Reusable connections, no adhesives
- Integration in asset of Core enclosure (mounting from the back)
- Integration of a Qi wireless charging coil
- Design suitable for (Recycling Avenue) ABS injection moulding
- Design requires not more than three moulds

Key functional requirements

- IP67 sealing
- Excellent antenna performance
- Retrofitting the TRACK to existing assets using a bracket (mounting from the front)

7.1 Product architecture ideation

Disassembly strategies

Keeping in mind the existing design goals, the first new goal about decreasing the disassembly time has the highest priority as it forms the basis for successful introduction of the circular loops (except reuse) (see figure 14 in section 3.3).

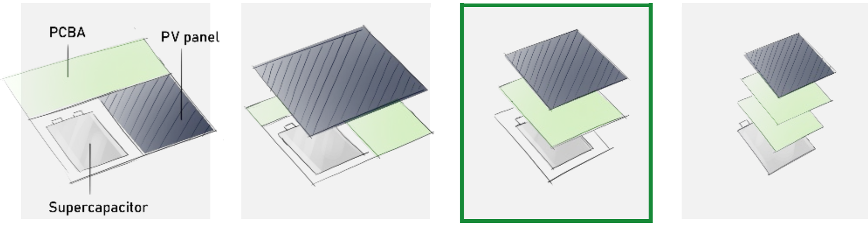
To achieve this goal the disassembly wish list from section 4 and the disassembly map of section 3.2 show aspects that will need to be improved in the disassembly experience. Furthermore, based on the disassembly mapping method there are 3 main strategies (De Fazio, 2021) to reduce the disassembly time of priority parts for electronic equipment redesign: trimming, surfacing and clumping. The strategies are explained in figure 48.

STRATEGY	DEFINITION	EXAMPLE
Trimming	Shorten the time per step to reduce the overall time to priority parts.	Using a snap fit connection for the battery instead of an adhesive
Surfacing	Reducing the number of steps to priority parts such that the parts get closer to the surface	Disconnect the battery from the PCBA without having to unscrew the PCBA first.
Clumping	Grouping parts in subassemblies make priority parts quicker to access.	Take out all electronic parts using a single subassembly

Figure 48: Disassembly redesign strategies for priority parts

Packaging options

The components are defined for concept Core 5G in section 6.3.
For simplicity the Qi coil is assumed to be part of the supercapacitor component as both should be placed lowest and the antenna is part of the PCBA. Arrangement of components can be from in-plane to a vertical stack.



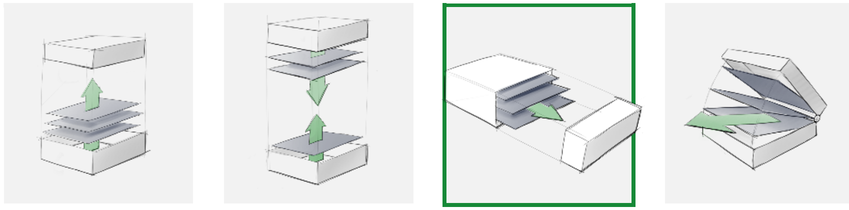
+ **Assembly of all components on a single substrate using a R2R production** + No chance of side impact damage + **Clumping of electronics**	+ **Large PV panel surface area** + Lower chance of side impact damage	+ Elevated antenna position + **Modular design: components can be removed individually**	+ High antenna position + **Most modular design**
- **Low antenna position affects performance on metal surfaces** - Large flat surface has chance of bending or breaking - Large mounting plane or small PV panel - **Form factor overlap with STEALTH**	- **Low antenna position affects performance on metal surfaces**	- Vertical wiring requires manual assembly - Chance of side impact	- **Smaller ground plane affects antenna performance** - Small PV panel - Vertical wiring of four components is most labour intensive - **Highest chance of side impact**

Packaging choice

The packaging configuration to continue with (3) is a similar configuration as the current TRACK Solar as it has no direct showstoppers and strikes the right balance between a high antenna placement, sufficient ground plane length and the PV panel surface area. This configuration does not benefit from a clumping strategy, but instead has a more modular design.

Accessibility options

Continuing with this packaging option, four accessibility solutions are proposed.



+ Opportunity for clumping of inner module + Direct access to priority parts	+ Direct access to priority parts	+ **Direct access to all components** + Support of flexible components	+ **Direct access to all components**
- **Additional inner housing part for clumping or deepest component takes more steps to access**	- Top components require additional fasteners or might fall out - Electrical connection complicates opening	- Wiring might be difficult to access	- **Complex hinge design**

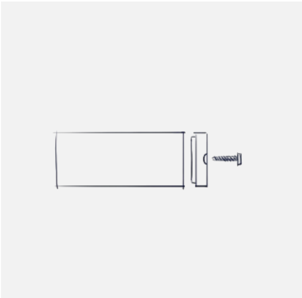
Accessibility choice

Although the current configuration (2) does not contain showstoppers, the best accessibility is predicted to be achieved with the 'direct access' (3) configuration, which provides direct access to each component (surfacing strategy). A horizontal configuration can provide better support for the flexible components through horizontal 'floors'.

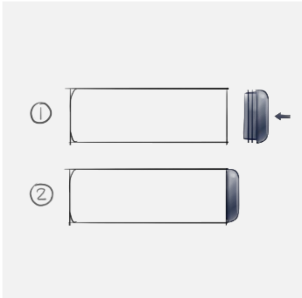
Sealing options

With this ‘direct access’ design, there are two types of sealing options:

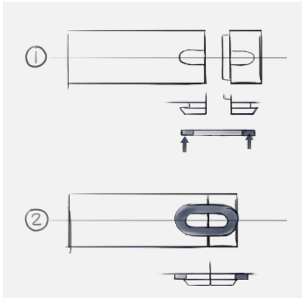
1. Mounting independent sealing options



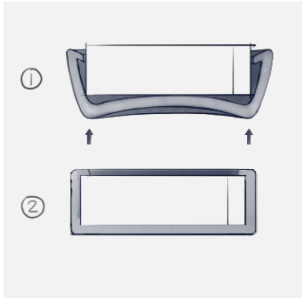
Screw



Rubber cap

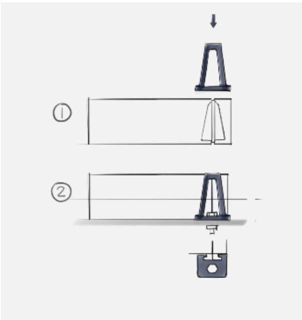


Click ring

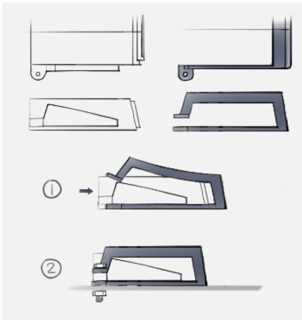


Silicone Case

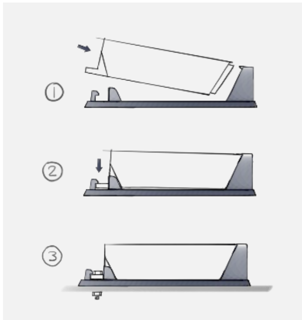
2. Mounting dependent sealing options



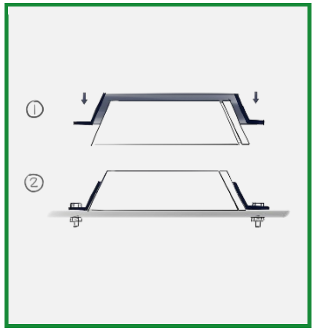
Side mount



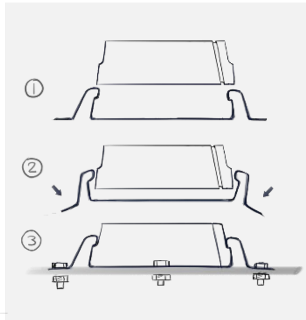
Snap fit



Docking station



Push mount



Gripper

Sealing choice

A mounting dependent sealing option was chosen as combining sealing and mounting steps could save disassembly time (trimming disassembly strategy). as the seal does not yet to be put under significant tension over a long period of time which is necessary anyway for mounting the TRACK to the asset. The push mount option is the most simple to use, most versatile and aesthetic execution of a two stage sealing method.

Combining the elements

Disassembly method

Combining the packaging, accessibility and sealing choices the fundamental vision of the embodiment for the TRACK Core concept and its (dis)assembly can be brought together.

In order to disassemble the product the user has to take the following steps, illustrated in figure 49:

1. Dismount the product from the asset
2. Remove the mounting bracket, which is only possible by moving it upwards, given that the design is chamfered (see the chosen sealing options in section 7.1). This provides access to the front cover
3. Removing the front cover provides direct access to the individual components
4. Now the components can either be exchanged or removed by sliding them out of the main enclosure.

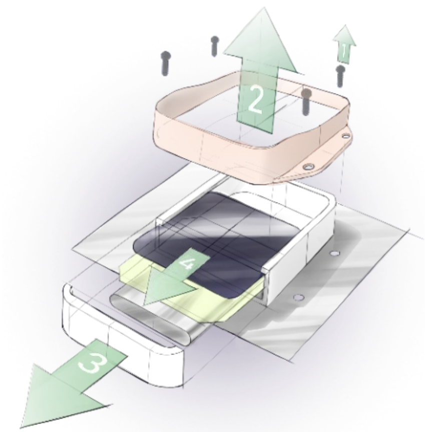


Figure 49: Illustration of TRACK Core product disassembly

Sealing

Given the directaccess design the assembly of the sealing would look like the illustration in figure 50a. These are the envisioned sealing assembly steps:

1. A seal ring is put around the PV panel and the panel with seal is inserted into the enclosure This seal should seal the top part
2. A second seal is put around the front cover which is then pressed against the main enclosure and the seal of the PV panel, hereby sealing the front part of the product.

Insight

Unfortunately this ‘direct access’ design does not work as the intersection of the PV and the front seal would likely lead to potential water intrusion issue as a gap could be formed (see figure 50b).

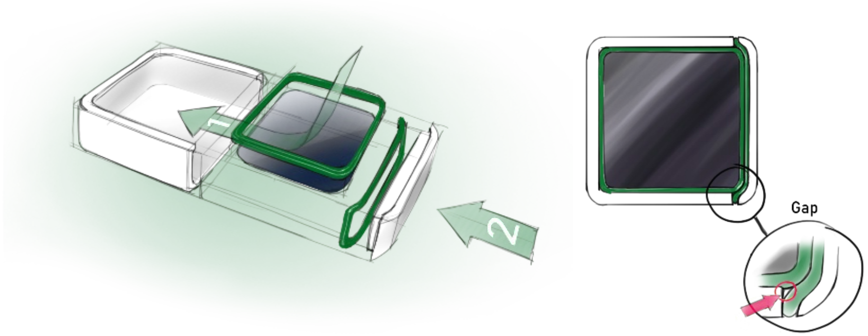


Figure 50: (a) Illustration of sealing assembly (b) Potential sealing issue

7.2 PV sealing redesign

A solution for the gap could be to seal the PV panel by pressing the seal against the top part of the enclosure. This means that the 'squircle' shape of the enclosure should be closed off on the top side by adding a crossbar (figure 51). In the new design the enclosure front panel could either be next to the crossbar or somewhat recessed such that top side is 'gapless'. In both cases the front panel seal will also be pressed onto the crossbar.

Working principle inside-out PV seal

With the addition of the crossbar the challenge is to find a way in order to press the panel vertically upwards given a horizontally designed architecture. A solution was found through extension of the front cover to the back of the enclosure. As the PV seal is slightly thicker than the leftover space between the two enclosure components, the seal will be compressed at all four edges once the drawer is slid in the main housing. The working principle is illustrated in figure 52.

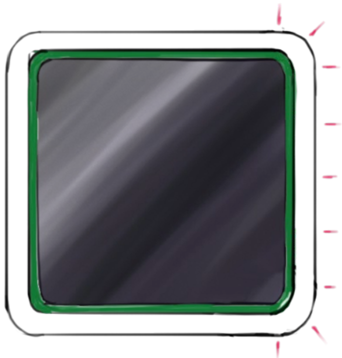


Figure 51: Top view of enclosure with addition of crossbar for PV seal

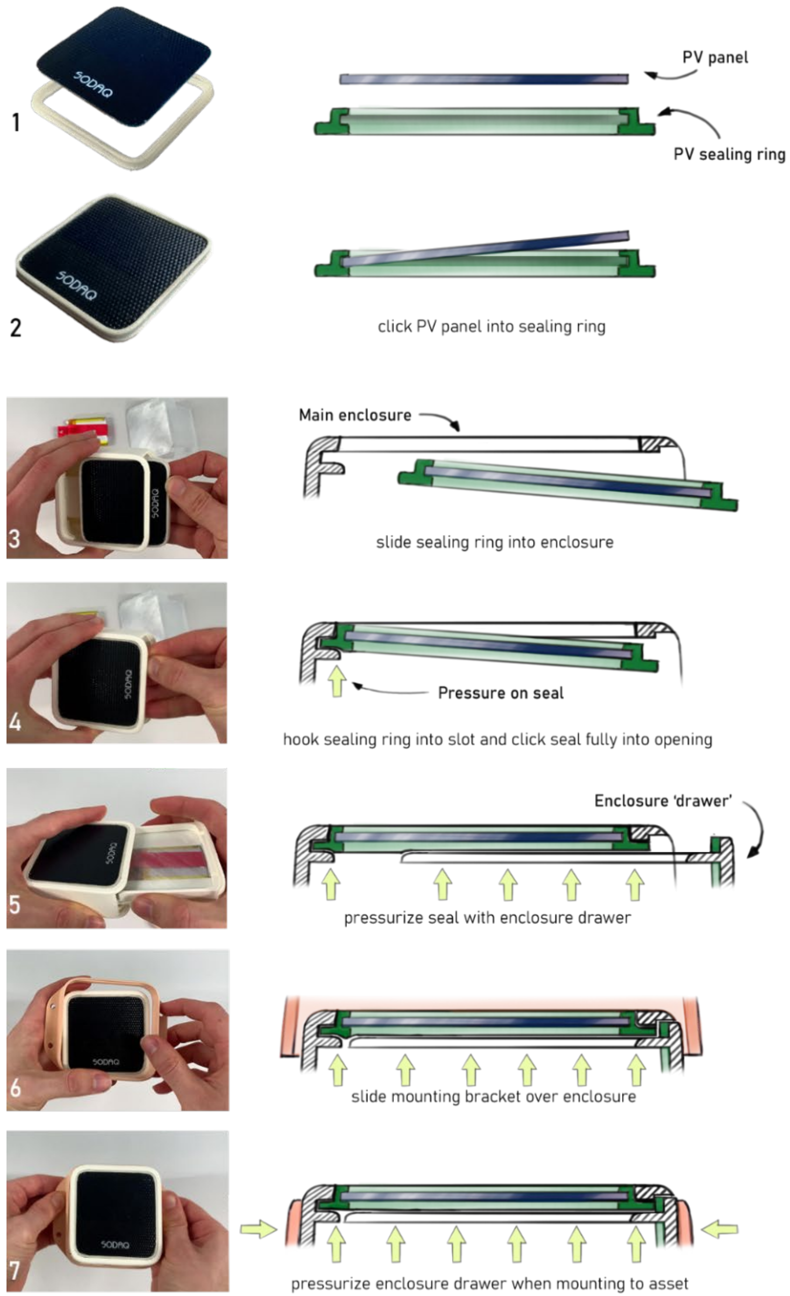


Figure 52: PV sealing performance during the PV panel assembly

Insights from PV seal design

When considering original PCBA positioning and the new PV assembly two issues were foreseen with the placement of the FHE board in the main enclosure:

1. With the new inside-out placement of the PV panel **vertical space to manoeuvre is required to get the panel out**. In the original direct access design shown in figure 53 the FHE board is directly underneath the PV panel, which makes taking out the panel with two hands difficult and might damage the SMD components.
2. **The flexible substrate could start to bulge when sliding the PCBA into the enclosure** and with limited interior space, there would be no easy way to correct it and the user might have to retry the action. Worse, the user may not notice that the PCBA is positioned incorrectly. This could lead to the circuit getting damaged through buckling or antennas getting compromised because they are left under an incorrect angle after the product is closed.

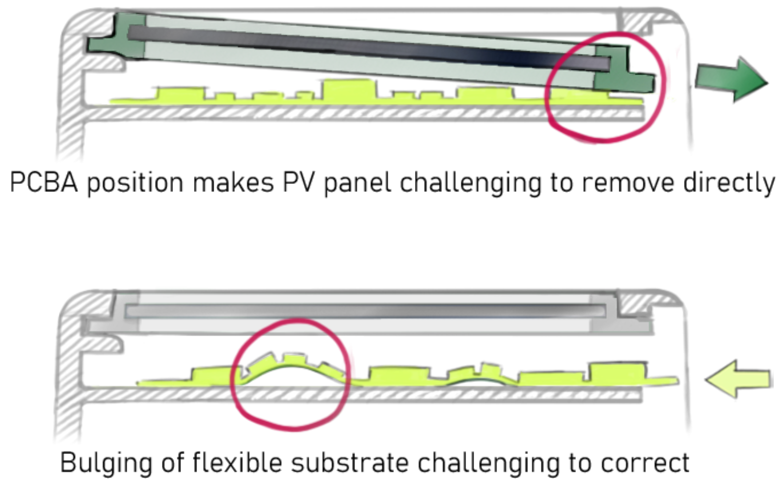


Figure 53: PCBA positioning issues

7.3 Components repositioning

PCBA in enclosure drawer

Both issues could be resolved by enlarging the space between the layers, however this could lead to a higher enclosure design, which is more prone to side impacts. Therefore a better solution would be to relocate the PCBA to the drawer side (se).

Supercapacitor/battery and Qi charging coil in drawer

In the original concepts for the TRACK Core from section 6.3 the cables and connectors would be integrated into the flexible PCBA to bring down the number of additional components and materials, hereby improving recycling. Also the Qi charging coil is attached to the flexible substrate as a clumping strategy. This means the Qi coil has to be mounted at the drawer side.

As the supercapacitor should be placed in between the PCBA and the coil, it would be the easiest to connect when the supercapacitor is positioned at the drawer side as well.

Additional benefits are that the newly created space at the main enclosure side will make it easier to remove the PV panel by hand and the supercapacitor can act as a structural element in the drawer sandwich structure. Figure 54 shows the resulting product architecture.

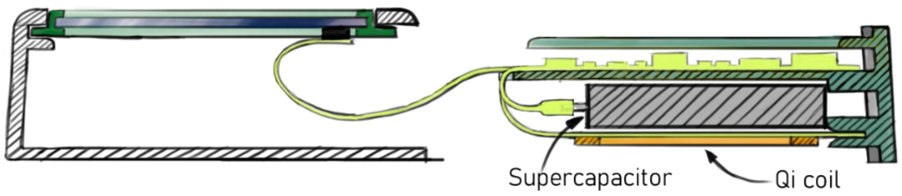


Figure 54: Section view of all component connected through integrated cable design

Insights from component repositioning

The following insights are illustrated in figure 55:

1. Bending resistance of the (cable) substrate makes that the PCB starts bulging which makes it difficult to pin the component in down while closing the product
2. Bending resistance of the substrate makes that the Qi charging coil will sit under an angle after assembly and could hit the main housing when closing
3. The coil is pulled out of its enclosure slot
4. PV panel cable can be difficult to connect without pulling the PCBA out of the drawer
5. Taking out a pouch cell could hit the Qi coil cable

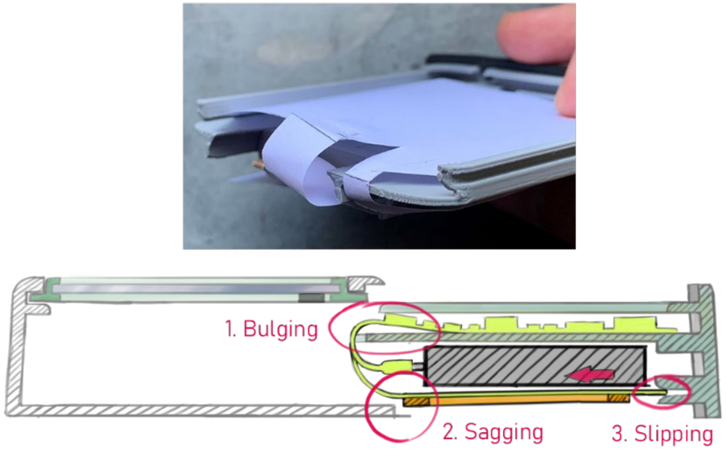


Figure 55: Section view of all component connected through integrated cable design and bulging PCBA

7.4 Folding PCBA concept

To counter the unwanted bending of the substrate and the cabling, a solution was found by assembly of a prefolded PCBA and slide the component in the matching hooks and guiding curves.
Furthermore, a solution was found to improve the (dis)assembly experience of the PV panel by using a spring-loaded sliding connector. For every improvement the issue that was uncovered as a result from the component repositioning the corresponding insight number is indicated in brackets. This resulted in the following process in figure 56.

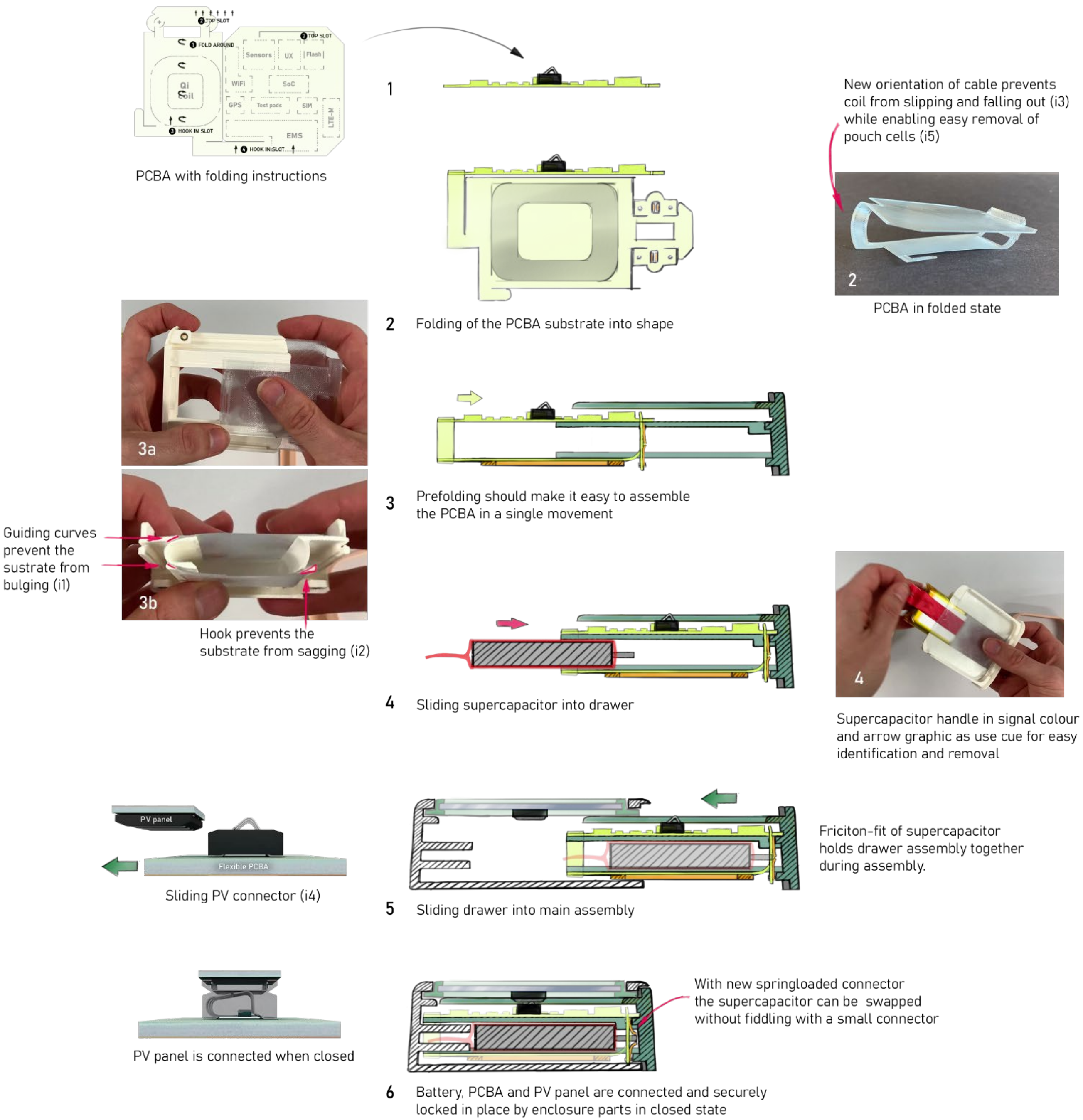


Figure 56: Illustration of folding PCBA improvements per assembly step

Insights from folding PCBA enclosure

1. A complete disassembly and assembly time is reduced significantly compared to the TRACK Solar
2. Unfortunately, the assembly process of the PCBA and charging coil turned out to be more complex for users than expected and did not result in correct placement in one go.
3. Battery/supercapacitor (dis)assembly was easy
4. Uncertain whether spring-loaded battery connection would work reliably as it is an unconventional method.
5. Design no longer allows for direct access to PCBA, as the battery/supercapacitor has to be removed first.
6. Crossbar seems prone to bending which may affect sealing performance of PV panel and drawer (figure 57)r.
7. Current sealing design of PV panel might not work with flexible emerging PV panels planned for the TRACK Core 5G

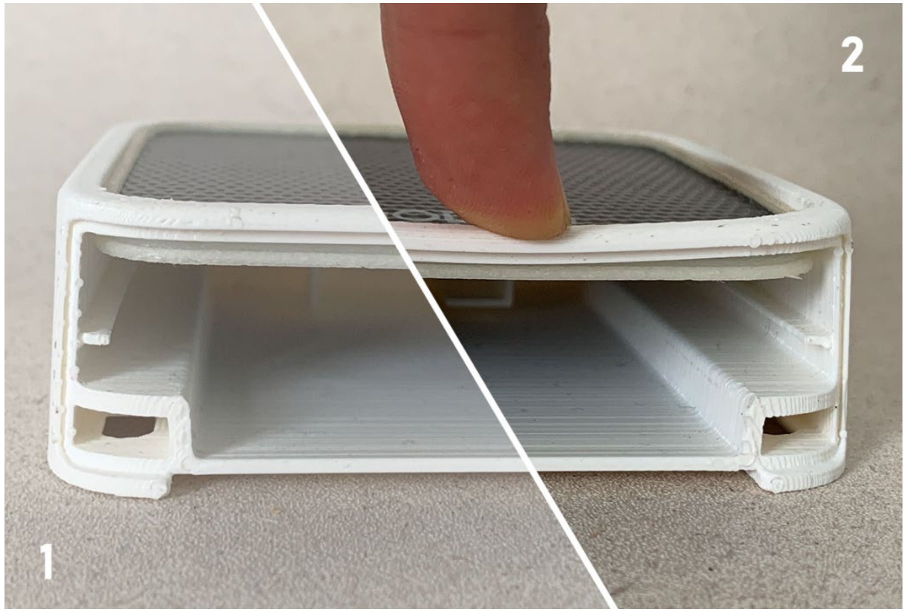


Figure 57: Crossbar exhibits some flexibility in the z-direction under pressure

7.5 Final enclosure redesign

Transparent enclosure with single seal

In a quest to find a solution to the flexibility of future emerging PV panels, a solar powered earphone product with a flexible DSSC panel was disassembled (appendix I1). The main product assembly has similarities to the drawer accessibility concept for the Core. While no specific sealing is present around the PV panel, the panel is nonetheless pushed onto the main 'wedge shaped' enclosure by means of an internal enclosure layer. Applying this principle to the current enclosure design would mean that a new supporting layer in the drawer has to be added (with a cutout for the sliding PV connector).

At the same time a solution should be found for the bending of the crossbar. In the end the decision was made to tackle both issues by closing off the top part of the enclosure and use transparent plastic for the PV panel. Through further reduction the number of seals this design would also be the safest option to achieve a IP67 rated product in this project. The application of a transparent top enclosure in combination with PV panels was identified in a competing asset tracking product (appendix I2). In this product the transparent enclosure is coated by layer of paint apart from the area directly above the PV panel to protect the electronics from exposure to UV (sun)light. The function of coating is taken over by the exterior mounting bracket in the Core or by frosting of the plastic. The result is illustrated in figure 58.

Replaceable battery

It turned out that the disassembly procedure of the enclosure was easy enough to justify the decision to focus on battery replacement instead of charging the device wirelessly. After the battery is swapped the client can charge the battery fully using a charging station and use the charged battery later for a future battery swap.

In this respect it is also good to note that by using a supercapacitor in a future Core model recharging during the first lifecycle of the product is likely not needed, as supercapacitors typically can handle significantly more charging cycles than a LiPo batteries. This also adds to the argument that a integrated charging solution is no longer necessary to include.

Clamp connector design

By removing the charging coil, the connector solution to the battery, which was part of the coil plane would need to be rethought. Moreover the current connection redesign was already a point of discussion (insight 6). Also the PCBA mounting solution which was done through the friction fit of the supercapacitor and would no longer function as a way to prevent the PCBA from falling out of the drawer during assembly, so this must also be rethought.

The key in the final redesign of the TRACK is therefore the introduction of metal clamp connectors. They functions both as a electrical connection and as a way to clamp down the PCBA and battery/supercapacitor, which prevents them from falling out during assembly. The clamping design could result in an uncomplicated assembly that further reduces the (dis)assembly time and incorrect assembly actions.
The clamp connector would also work for the PV panel and replaces the sliding connector component.

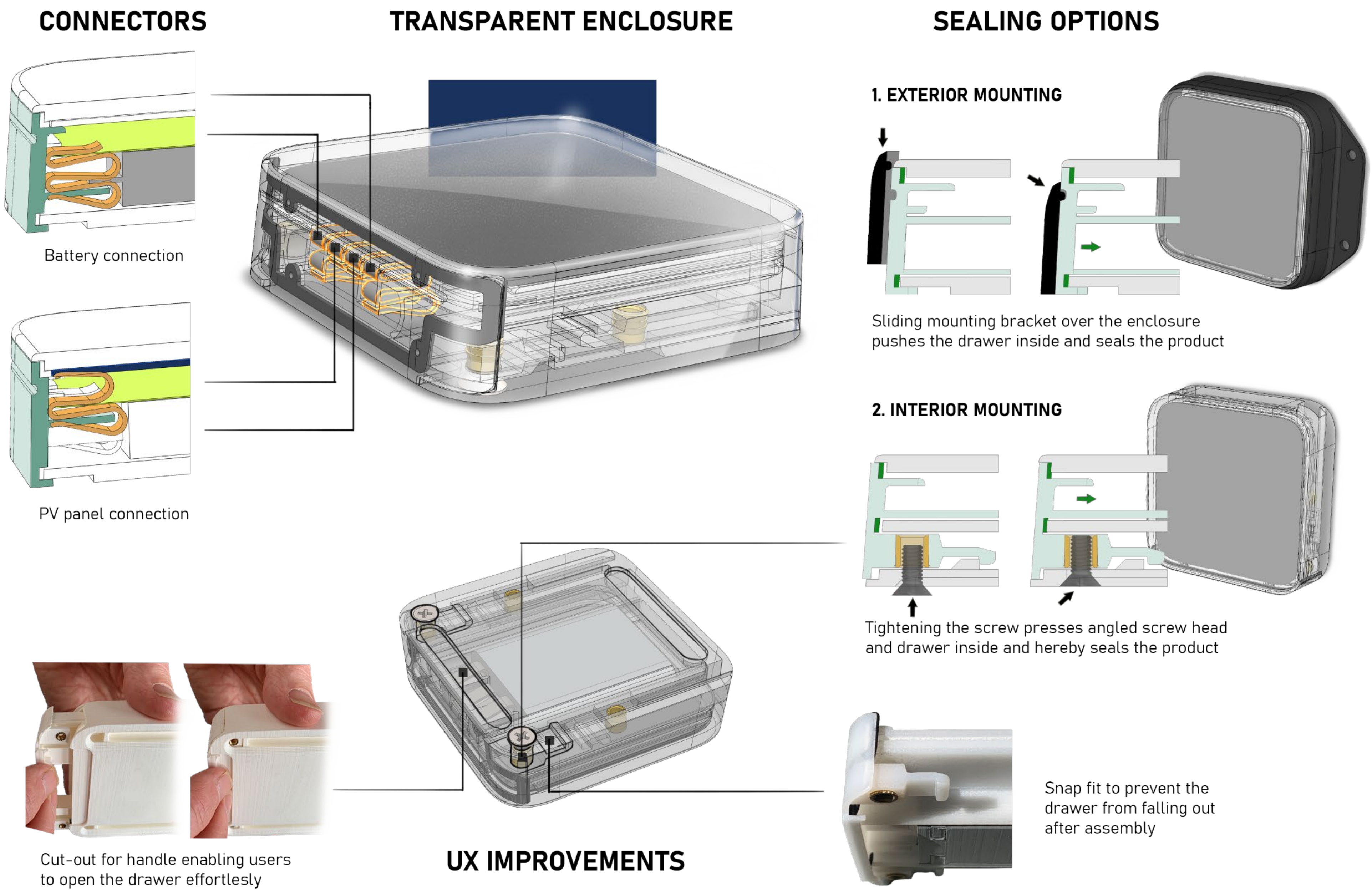


Figure 58: TRACK Core enclosure design features

Return of the 'direct access' design

With the new clamp connector design and return to a single layer substrate, all electronic components can now be taken out independently. This means that in this iteration of the redesign, the concept returns to the 'direct access' accessibility concept from the ideation phase. It works as illustrated in figure 59.

Usabilty improvements

During disassembly tests it became apparent that the opening of the drawer was notably tricky as users tried to pull out the drawer at the edges with their finger nails with mixed success. In this design the 'handle' is placed at the underside of the product and the drawer can be opened by placing four fingers in the cut-out and pulling it out easily.
Secondly, a common occurrence was that the drawer fell out of the Enclosure during assembly and disassembly. An easy solution was to add a snap fit type connector to the drawer to hold it in place.

Sealing options

With the new design, the sealing is reduced to waterproofing of the drawer. This can be done in two ways depending on the mounting of the product on the asset:

1. In the case of retrofitting the Core to an asset, the exterior mounting bracket will seal the product by sliding it over the product and then mounting the bracket to the asset. A detailed illustration of the sealing process is provided in figure 60.
2. When the Core is integrated in the asset or if it needs to be easily swapped and an interior mounting bracket is used, the seal needs to be pressurized by tightening the countersunk flathead screw.

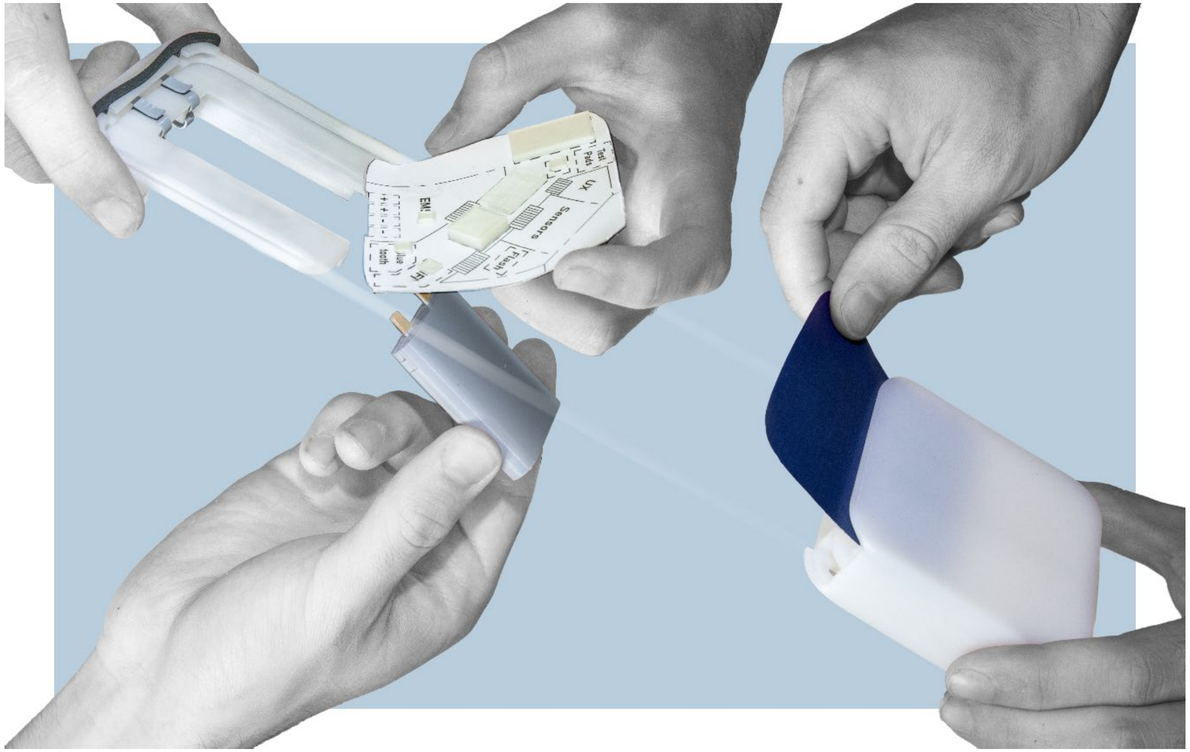


Figure 59: TRACK Core 'direct access' accessibility concept in action

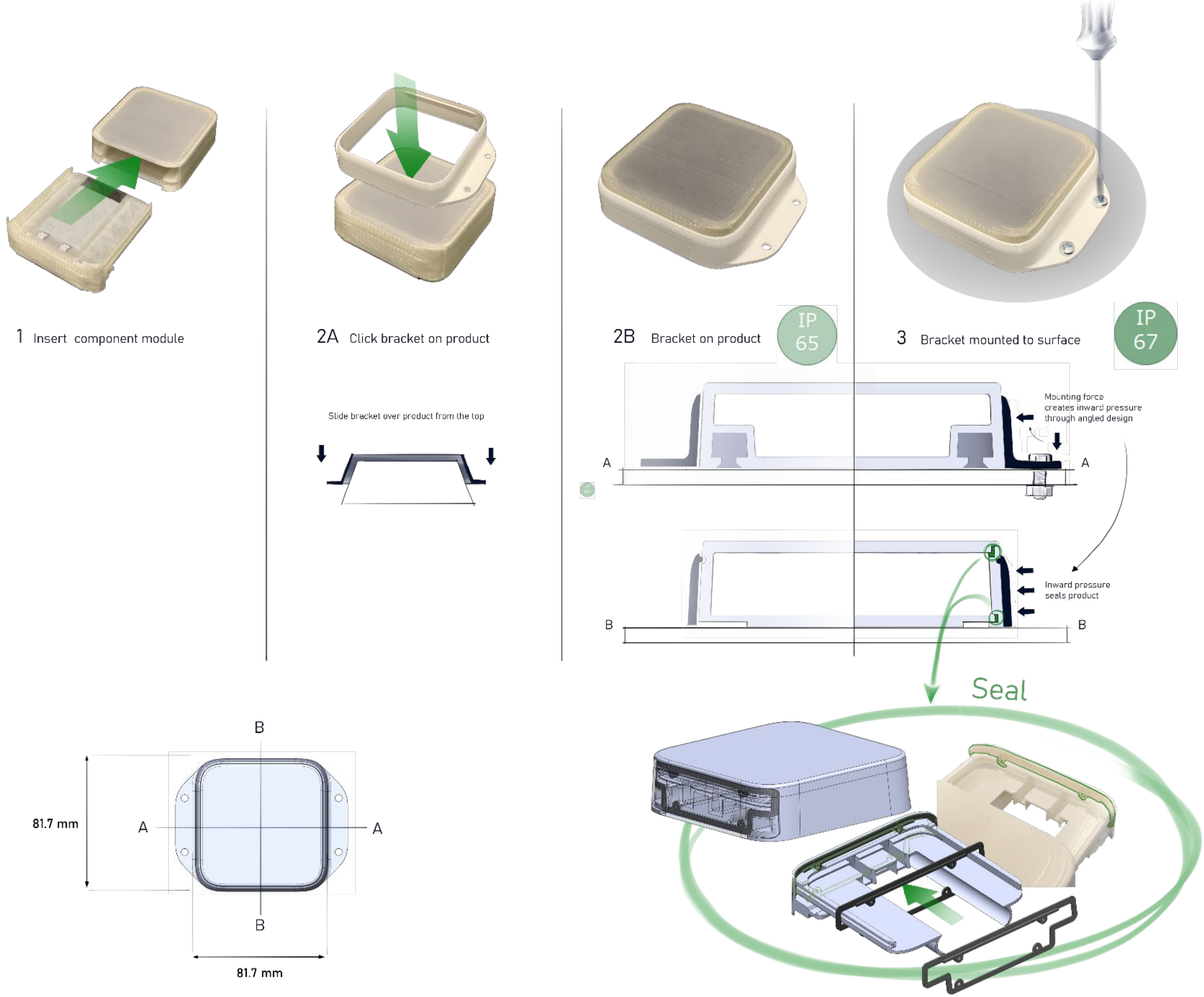


Figure 60: TRACK Core exterior mounting sealing

New asset mounting options

To enable circular loops the product has to be removed from the asset first. To improve circularity TRACK Core the mounting options are also revisited and a overview of the new options is illustrated in figure 61.

Customizable exterior bracket

Initially an exterior mounting bracket was envisioned that provides sealing through secure mounting of the product to the asset's surface. The bracket has to be put over the product from the top; this way the Core product cannot be stolen without first dismounting the bracket from the asset.
The case of the bracket design for the seedpack proves that a one-mounting-fits-all approach does not work. If the number of assets is significant enough it will be possible to invest in a custom injection moulded bracket product. To address a wider market of clients with a more limited number of assets, the customized brackets for those assets could be 3D printed.
To solve the potential workload of custom designed brackets a generative design tool can be employed in which the mounting points serve as input and a 3D printable mounting solution comes out.

Interior bracket for asset integration

One of the visions for the new TRACK Core was better integration into assets, which might be the case for a future version of the seed containers. To mount the product securely and out of view in the reserved space, the mounting points would need to be positioned at the underside of the product. The result is an interior mounting bracket with mounting points can be inserted into the dedicated rail. Various lateral mounting point positions will be available.

Swappable interior bracket

A further opportunity that arises is the option to make a mounting bracket that enables the product to be swappable such that the tracking device can be easily taken off and used for another asset or to change batteries quickly.

Improved circularity

- Detachable and printed interior and exterior mounting brackets make it easy to reuse the Core at the end of its first lifecycle. For the new asset it will be mounted to in its new lifecycle SODAQ can print a new custom bracket.
- Integrating the product in an asset means that the number of mounting points can be reduced from three or four to two, as the chance of side impact is absent. This reduces the dismounting time and increases the chance of product reuse.
- The opportunity that all mounting issues with custom bracket solutions makes that problematic adhesives can be a thing of the past.

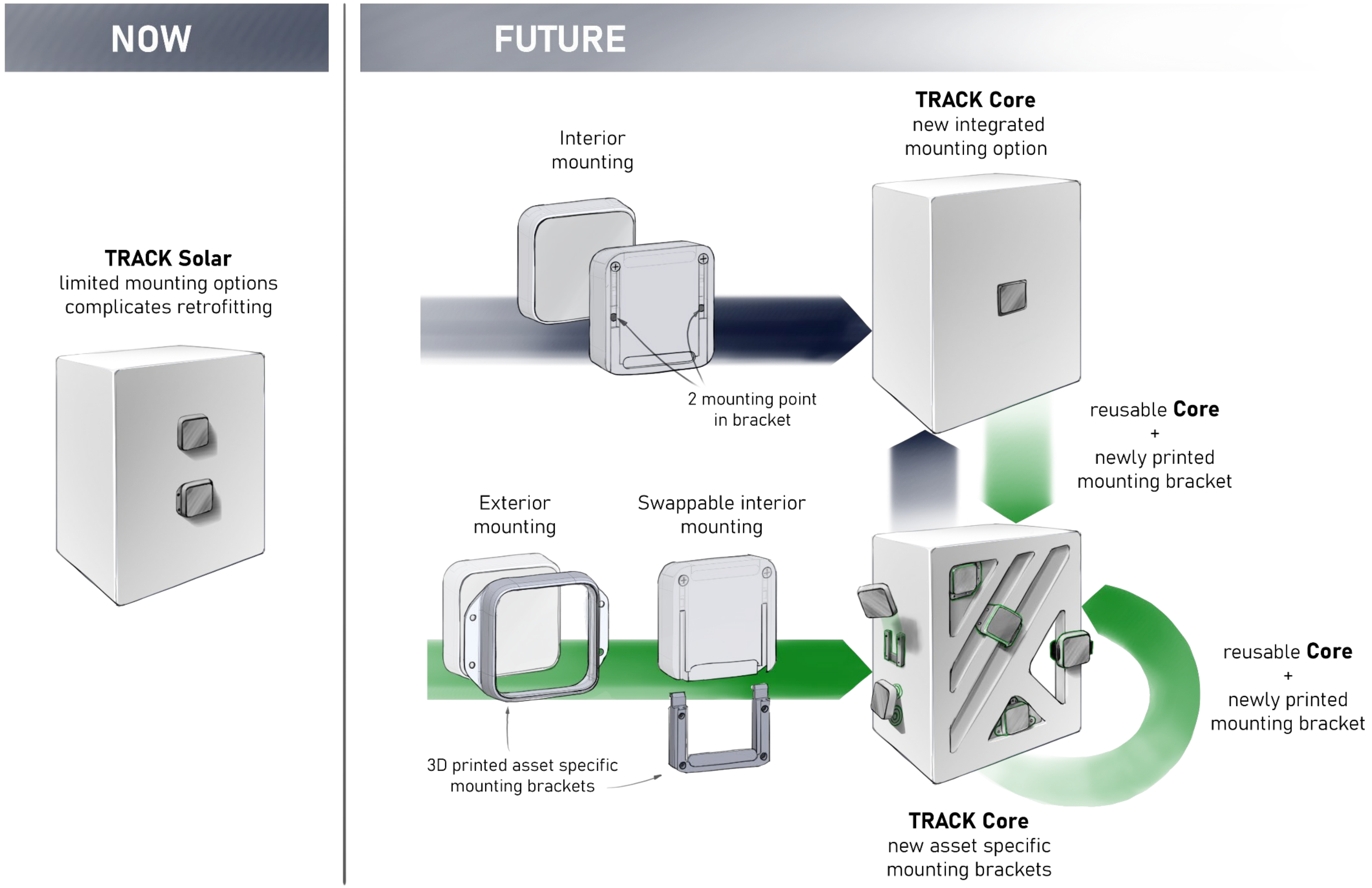


Figure 61: TRACK Core asset mounting options

8 TRACK CORE UPGRADABLE PCBA

With the choice for the Core 5G concept the goal was to investigate the opportunity to upgrade the PCBA to extend the lifetime of the ICs on the PCB. In this chapter the theory on modularity will discussed and the application of modular product design by Fairphone. Then a first modular proposal for the layout of the TRACK PCBA is discussed and two iterations for implementation.
Finally the upgrade process is mapped.

8.1 Modularity in hardware design

Modularity is a common method used to improve reparability, recyclability, but also upgradeability of an electronic product. The goal of a modular design is that the electronic components with shorter lifetime should not limit the lifetime of other parts.

Modular hardware strategies

9 types of modular design mainly applied to smartphones design concepts can be distinguished (Schischke, 2019). The 6 most revelant strategies are described here:

Material modularity – Detachable components for easy recycling (e.g. user-replaceable battery)
Do-it-yourself repair modularity – Module design of priority parts aimed at replacement with common tools by laymen/users (e.g. Fairphone)
Internal modularity for serviceability – Division of internal electronics into modules, attached to a main board; serviceable by professionals (e.g. smartphone logic boards)
Repair modularity on board level – Further division of electronics up to individual components level modules, attached to main board (e.g. PC processor sockets)
Upgrade modularity – Modules designed for long-term compatibility of hardware interfaces and software to support future upgrades (e.g. Fairphone camera upgrades)
Platform modularity – Configuring a design with modules offering different functionality connected using common platform standard (e.g. Grove connection system)

Connector design

The most evident design change in a modular product is the need for connectors that provide mechanical and electrical contact between modules (Schischke, 2019). And although the connectors might only be used a few times, it can still pose a weak spot of the product. This means attention has to be paid to the reliability and durability aspects, while good ergonomics can help to prevent damage during reprocessing.
Generally there are different connector designs to chose from:

- Standard press-fit board-to-board connectors such as the mezzanine strip connectors with a flex PCB acting as hinge and cable (figure 62a)
- Friction fit connectors as the current JST connector (figure 62c)
- Non-permanent connectors such as spring contacts or spring-loaded PoGo pins (figure 62b)
- Debondable adhesives
- Connectors with permanent magnets

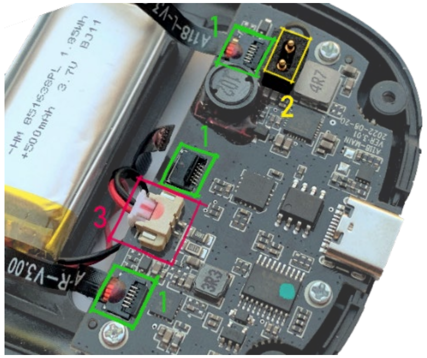


Figure 62: Example of connector designs (1) FPC, (2) PoGo pins and (3) JST

Software upgrading

Another opportunity for upgrading a product's functionality is to leverage the power of distributed computing in the cloud. The computational power of the cloud allows for more flexibility and adaptability in computing power and memory allocation that might be required in future complex (machine learning) algorithms (Meloni, 2018). A good example is the u-blox CloudLocate (u-blox, 2023) service where GPS position calculations are offloaded to the cloud, hereby lowering hardware power requirements. This also means that less powerful previous generation hardware is still good enough to use with more advanced software

Fairphone 4 case study

Modular strategy

The main strategies used by Fairphone are **do-it-yourself repair modularity** for the screen, USB port and the microphone and **upgrade modularity** for the camera of the Fairphone 2 and 3 (see figure 63).

It is interesting to observe that the module for the camera of the Fairphone 4 has become much bigger compared to previous generations and now not only includes the camera but also the microphone and 5G antennas (Fairphone, 2023). On the other hand, the other modules have been designed with less components and have become smaller. Although this helps to increase the financial margin on the module, the electronic components are to be transferred to the Core module.
However "with the design choice of reducing the peripheric smaller modules [compared to Fairphone 3] it is even more important to be able to

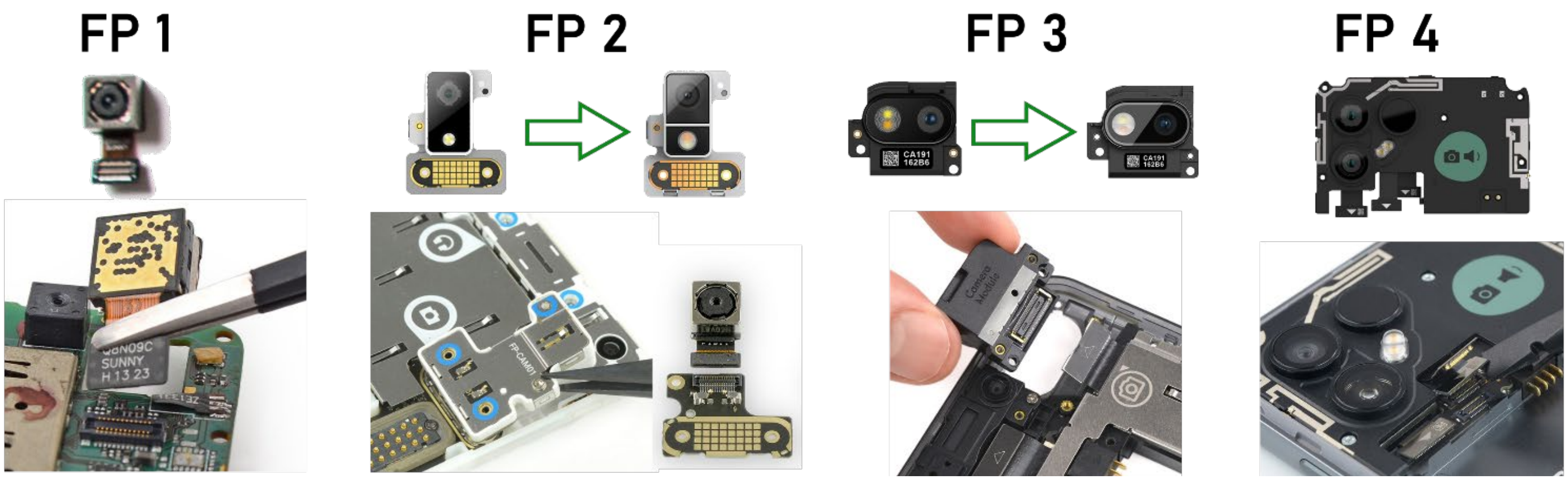


Figure 63: Fairphone camera module upgrades and the mezzanine strip connector based connection iterations

perform board level repair when a component in the mainboard fails" (Proske, 2022). It is unclear however if and if so how the **repair modularity on board level** design strategy has been implemented.

Connector design

As shown in figure X, the design of the connector has undergone a number of changes. While the camera of the first generation uses the standard mezzanine strip connector, the second generation uses a proprietary spring-loaded connector. Interestingly, when looking at the inside of the Fairphone 2 camera housing you will find a lens that is still connected to Fairphone's spring-loaded connector via a strip connector.

Although considered the summum of repairable (smartphone) design at launch, with an iFixit Repairability Score of 10/10 (iFixit, 2015, Fairphone later decided to reverse course and reintroduced the standard strip connector in their third generation phone.

Furthermore the number of connectors has been subject to change. "The design of Fairphone 4, learning from previous iterations, has reduced even further the amount of connectors. Currently the amount of board to board flexcables is comparable (if not identical) to most smartphone models of the latest generation" (Proske, 2022). However, looking at iFixit repairability scores of the latest generation smartphones shows that even with the same building blocks, Fairphone is still ahead of its rivals in this department.

Modularity overhead

The additional fasteners (screws), pieces of housing for the modules, flex boards and press-fit board-to-board connectors which are needed to enable modularity are called 'modularity overhead'. The modularity overhead should be minimized as it adds to the Bill of Materials (BoM) and thus cost. Although the additional cost is unknown, the impact of the modularity overhead to the Fairphone 4's footprint is only 1 %.

Long-term compatibility

The introduction of camera upgrades for two generations of products shows that Fairphone has developed a strategy that allows them to offer for 'long-term' compatibility of the chosen hardware interface. Although you could argue that long-term is quite relative. The camera upgrades for the Fairphone 2 and 3 are introduced respectively around 2 and 1 year after the original product launch. This means that the next camera component module would probably already have been in development during the finalization of the original phone parts.
But how to support for a camera component that is much further in the future? Do you need to reserve empty pins for possible future functionality for example?
One could argue upgrading becomes somewhat harder for the Fairphone 4 as the camera module has increased in complexity and now incorporates a multitude of components. It is possible that Fairphone has changed their strategy after dropping their proprietary connector already a generation earlier.

Software upgrades

While the hardware upgrading strategy might be more of a carefully planned marketing strategy, the software support of 7 years (Fairphone, 2023) is impressive, especially compared to the lacklustre update support policies of the major Android smartphone manufacturers.

Conclusion

There are a number of strategies that support the choice of a modular PCBA design in theory such as **material modularity**, i**nternal modularity for serviceability** and most relevant for the TRACK: **upgrade modularity**. The case of the Fairphone shows that there is business opportunity for upgrading when taking into account that the upgraded component will be released on the short term.

8.2 Modular upgrade strategy

One of the main long-term failure modes of the TRACK could be product obsolescence due to mobile network end-of-support. A potential solution would be to upgrade the network component instead of replacing and disposing the complete PCBA together with functional and high impact components that are not yet obsolete.
To this end **upgrade modularity** and possibly even **internal modularity for serviceability** strategies can be used. First the feasibility of the strategy is explored by discussing a proposal for a modular PCBA with SODAQ hardware engineers

TRACK PCBA modules

Looking at TRACKs current PCB component types, it would be logical to make a division of components on their functional characteristics (communication, processing, UX, sensors, energy management and storage). After talking to SODAQs hardware engineers the following modules were envisioned:

- **Communication module** The processor System-in-Package (SiP) also houses the modem which is designed to match the antenna. Therefore the processors and the antennas should be seen as one component that needs to be upgraded if the network standard is no longer available.
- **Energy management module** .The battery, PV panel and the USB-C port are connected to the Power Management IC (PMIC), which takes care of supplying the circuit with a constant voltage.
- **UX module**. The button and LED components are grouped into one module as they likely have a functional life that is far beyond the rest of the components.
- **Sensor module** The sensors are a module because of the changing need per client. Sensors not installed for the client of the first use cycle can be changed to meet the needs of the client of the second use cycle. It is also possible to replace the sensor module with some other module as future versions will rely more on externally connected sensors.
- **Flash module** The flash is decoupled from the rest as it is uncertain what the condition will be after a first life. It might need to be replaced.

SODAQ upgrade modularity discussion

After the PCBA was divided into modules the result (figure 64) was presented to SODAQ hardware engineers. Although they agreed with the divisioning they did have reservations about the need and the potential implications for the design process and doubts about the business model.

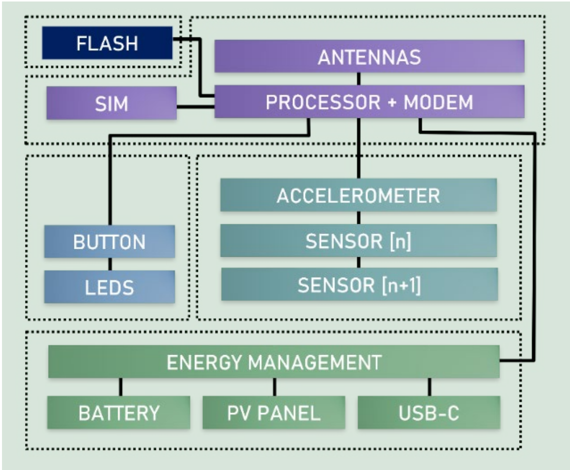


Figure 64: TRACK Solar proposed modules for PCBA components

OPPORTUNITIES FOR SODAQ

Fits the goal of circular product design: maintain product integrity with minimal investment
Life time extension
Some components have a longer lifetime than others and on traditional PCBAs the shortest lifetime component will dictate the functional life of all other components. In a modular design the target components can be exchanged such that the other component are kept in use.

Cost-effective component upgrade
In case of component change (e.g. replacing a LiPo battery with a supercapacitor) only the corresponding module (e.g. BMS) will need to be exchanged instead of the complete board.

Reduces sourcing risk and facilitates prolonged product support
The modular design makes it easier to keep spare parts in stock as availability of original components dwindles over time. Modules contain less components, which decreases the chance that a component becomes unavailable and the physical segregation in modules avoids a redesign of the complete PCB layout.

Allows access to low-cost products and materials
SODAQ can acquire functional products and components at lower cost whereas the carbon intensive sourcing and production of new electronic components might become subject to carbon taxes and the industry might be pushed towards using more fair trade sourcing of minerals or using (more costly) recycled content in new components.

CONCERNS BY SODAQ

Costs
Modularity overhead (extra components/boards/development time)
“I do not want to place a burden on the development process by thinking about packaging requirements for future developments”

Labour costs associated with upgrading process
“ I do not see the upgrading being done, the labour costs will be too high. Who would be willing to pay for it?”

Marketing of upgraded product
Uncertain market demand for older generation or reprocessed products
“I always would want the latest and greatest and I expect that is what our customers would want too.”

Inflexibility of modular strategy
Backwards compatibility requirement limits integration of new parts
“The PIN-OUT number and type for every new generation of components (e.g. processor SiC) can change significantly. It is impossible to anticipate this far in the future [5-7 years]”

Predicting future developments is not an exact science and heavily relying on these development so far into the future for the business model to work is risky
“I have been in this company for almost 10 years now. I could not have imagined 10 years ago that the products we are building right now would be possible.”

Conclusion

The proposed divisioning of the modules of the PCBA was considered logical by the SODAQ hardware engineers. However during the discussion it turned out that they were sceptical if the benefits of the concept could outweigh the additional costs and other uncertainties. Focussing on **internal modularity for serviceability** or **upgrade modularity** therefore were not considered viable pathways.

On the other hand there is the goal of this project, which is to lower the environmental impact of the electronics per location message. A modular design is one of the most logical ways to achieve this as it provides an opportunity to lower the demand for new electrical components during repair and upgrading. Especially the use of ICs, which are identified as the highest impact components, can be restricted this way.

For the project this means that a desirable project outcome should be about retaining and investigating the opportunities of modularity while finding ways to lower the concerns of SODAQ about a more modular PCBA design for the TRACK.

New design goals for upgradable PCBA

Cost-effective reprocessing steps

To bring down the cost of potential reprocessing actions such as upgrading, the process should be easily executable by the technical staff of the client, in minimal time and with minimal means. This implies, for example, that if the reprocessing process involves certain non-standard tools, SODAQ has to ship them together with the new parts to the client.
Also investment in modularity overhead (of which parts later turn out to be left unused) should be minimized.

Flexible modular design

The new modular design has to become more flexible because the lifecycle of the product is relatively long and it is easier to adapt to unforeseen future requirements and additional components with a flexible PCBA design.
Additionally, SODAQ does not (yet) have enough data to predict the failure of key electronic components over time and this will result in the need for investing in modules and modularity overhead that will possibly never be used.

8.3 Initial ‘cut and paste’ PCBA upgrade proposal

New modular PCBA design strategy

The new flexible PCBA in the TRACK Core and the use of anisotropic film in the FHE field might unlock new opportunities currently not explored in modular electronics design. For example by studying the material qualities of flexible substrates, the opportunity arises that the substrate can be cut easily even with hand tools.

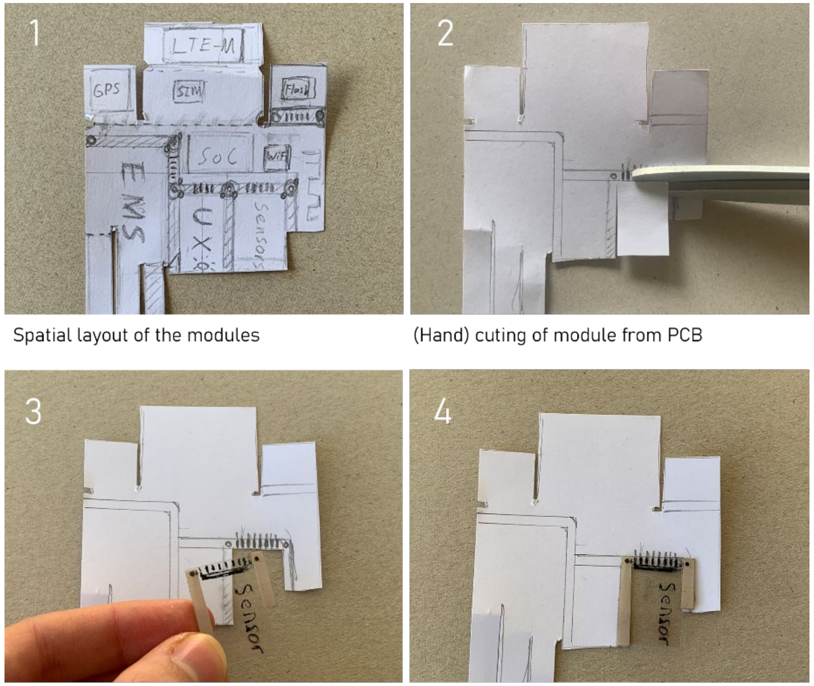
To this end a new design strategy is proposed for modularity of the PCBA which improves upon both the cost and flexibility aspects.
Traditionally a modular design consists of physically separate modules which are connected using board-to-board, board-level connectors/sockets. However given the cutting opportunity later in life a new type of modular design for the PCBA is imaginable where the board layout can be divided into these modules, yet the modules remain part of the same board. This means the modular PCBA can be manufactured without any initial modularity overhead, extra cost for (manual) assembly or loss in reliability (from using connectors). Later in the product’s life it will be determined what modules specifically need to be separable, if any. This makes that the upgrading of the components becomes more flexible.

Cut and paste prototype

A simple prototype was made to illustrate the practical implication of the new design strategy and test whether the proposal could work. The steps are shown in figure 65. The idea was that the module that needs to be replaced for either upgrading or repair can simply be cut with a pair of scissors. The new component can be placed using a pre applied double sided anisotropic adhesive film for the electrical connection.

Insights from initial upgrade concept

1. The hardware engineers thought it was an interesting avenue to pursue as the additional costs are relatively low.
2. However they have reservations that cutting by hand would be reliable enough and not damage other components accidentally.
3. The alignment of the connection pads requires precision, which will be hard to do by hand



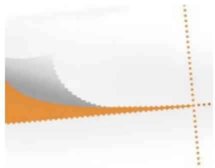
Spatial layout of the modules
(Hand) cuting of module from PCB
Pick new module and remove protective film
Attach new module on pads and sides

Figure 65: Cut and paste module replacement steps

8.4 Cut & paste concept in practise

Cutting tool options

Given the insights from the initial concept the focus for the second iteration is to find a more reliable and precise way of cutting.

WISHES	CUTTING TOOL OPTIONS			
	 **Hand cut tool** scissors, utility knife	 **Perforated cut**	 **Die cut punch**	 **Craft cutting machine**
Minimal investment by SODAQ Manhours or tool cost	**++ Clients own the tools already**	**++ No tool required, perforation is precut during production of board**	- Unique dies need to be made for all different module configurations	+ SODAQ already owns such a machine. Machine can cut any given shape
Compact dimensions Ability to ship the tool to the client	++ No tool needs to be shipped	++ No tool required	+ Compact dimensions	**-- Large intricate product and large accessories make it expensive to ship to a client**
Precision and reliability of cut Tolerance of tool, risk of incorrect cut	**-- Accuracy depends on motor skills of the user**	- Premade cut is very precise in theory but a 'clean' tear also depends on user motor skills	**++ Very precise if placed in a cutout of the shape to ensure correct position during cutting**	**++ Very precise if placed in a cutout of the shape to ensure correct position during cutting**
Usability of tool Familiarity with tool, risk of incorrect use	++ Everybody can use the tool	**- Tearing is a common method in packaging, but tearing the electronic connections is difficult**	++ Using the tool should be straightforward	- User needs to learn machine software tool
Throughput Speed of cutting	- Cutting requires full attention to task, can be exhausting for higher volumes causing errors	- Tearing requires full attention to task, can be exhausting for higher volumes, causing errors	+ Alignment of the board and punching does not require much attention and steps can be completely in a short time	++ Process can be automated for large volumes

Tool choice

The die cut punch was chosen to be the most suitable tool to be used in combination with the anisotropic tape by the client's staff through control over a precise cut. For the precise alignment and controlling the pressing force an additional press tool could be used that aligns the pads of the new component with the pads of the existing PCB.

Concept assembly steps

Bringing this together the 'cut and paste' concept could work as illustrated figure 66. There are still unknowns in the concept such as the design of the and the working principle of the align tool, but primarily the suitability of the anisotropic conductive adhesive for this type of application is important.

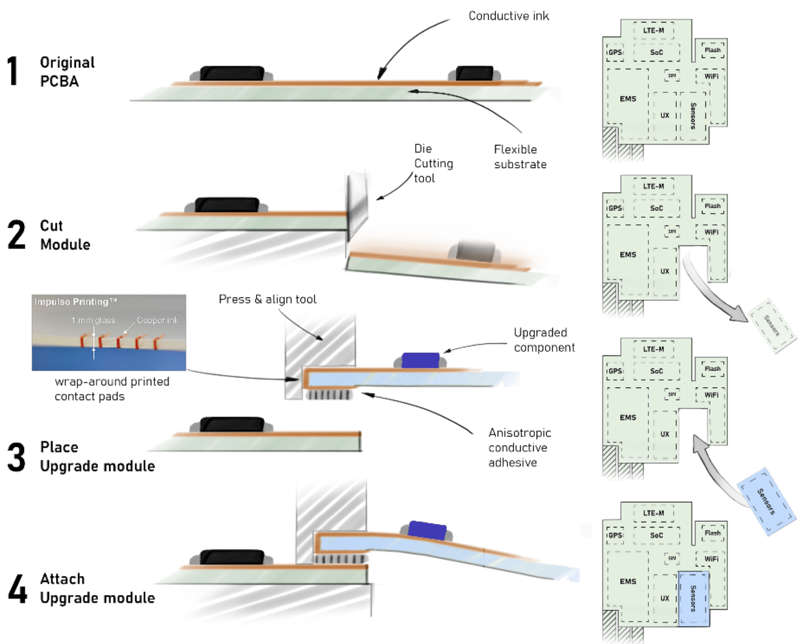


Figure 66: Cut and paste module replacement steps

Anisotropic Adhesive film initial test

Currently the anisotropic conductive adhesive is already in use in SODAQ prototypes to create a connection between contact pads of the battery and the flexPCB. However the contact pads of the envisioned module connection would be much smaller in terms of surface area and pitch.

To see if connection could still work and whether it could function as a way to replace soldering the material for easier recycling (see Core FHE recycling vision in appendix F6) was tested. The adhesive film of the company CondAlign was used for a test on a SMD practise circuit (figure 67). The goal was to compare the performance of the circuit with the conductive film with a traditional soldered circuit.

Unfortunately, while the soldered circuit worked as expected, the circuit with the adhesive did not work at all. Continuity testing over the component first on the legs of the components and then on the copper contact pads proved that while the component was fine the conductivity between the pads and the component legs was insufficient.

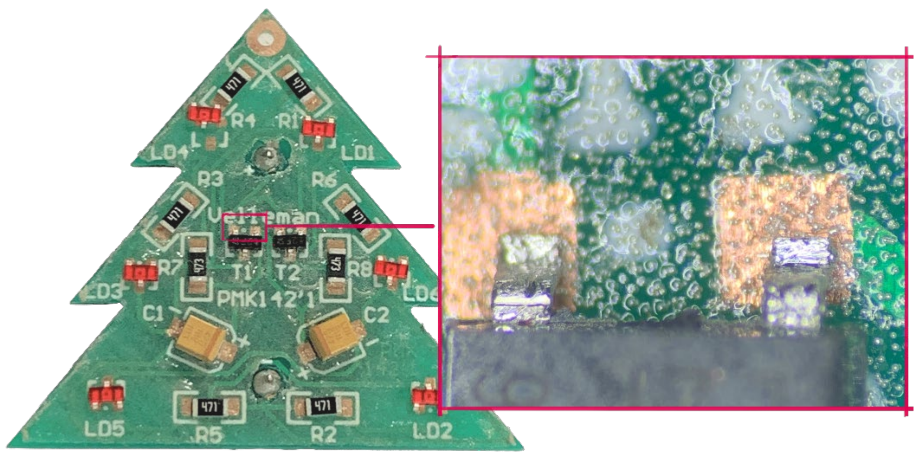


Figure 67: Anisotropic adhesive test with conductive vias in z-axis is clearly visible

Insights from anisotropic conductive adhesive test

According to the CondAlign hardware engineer visiting SODAQ, the conductivity issue might be related to a combination of the following factors:

1. The contact pads are not level with the masking layer surface of the PCB which leads to loss of contact (figure 68a).
2. Conductivity of the copper contact pads for smaller contact areas might not be sufficient. Ideally the contact pads would be gold or silver plated (see figure X in appendix F2).
3. The pressure applied by hand might have resulted in uneven pressure distribution, hereby disturbing the alignment of the conductive chains which leads to loss of contact within the adhesive (figure 68b). Applying the film using a squeegee with a felt tip is therefore recommended.

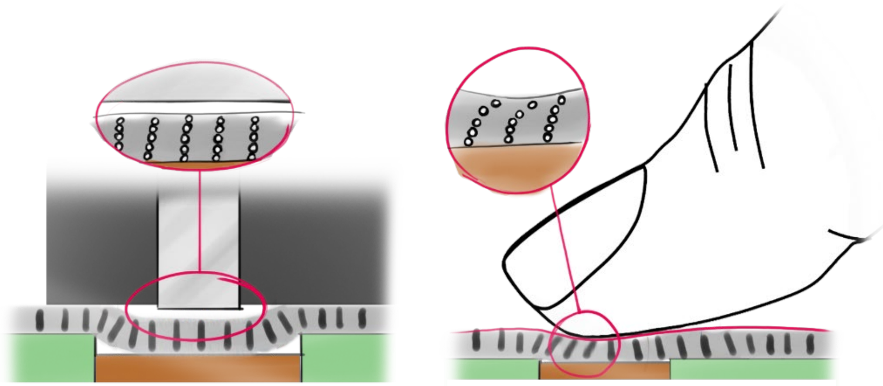


Figure 68: (a) Loss of contact issue by gap (b) Disturbing the conductive chains with the finger

New anisotropic adhesive film test

For the second attempt a new SMD practise board was used with silver plated contact points that seemed level with the masking layer and the adhesive film was applied using the application instructions provided by CondAlign (the resulting sample is shown in figure 69). Unfortunately the continuity test still showed no indication that the conductivity issue was solved. Therefore the decision was made to abandon attempts with this material for the use in the PCBA concept.

During the interview with the company InnovationLab (appendix F4), the company also mentioned that they had problems with ensuring reliable connection with anisotropic adhesive and returned to using low temperature reflow soldering.
Condalign later stated that the company was developing adhesive with a higher density of conductive chains, aimed at more reliable component mounting which would be more suited for the application.

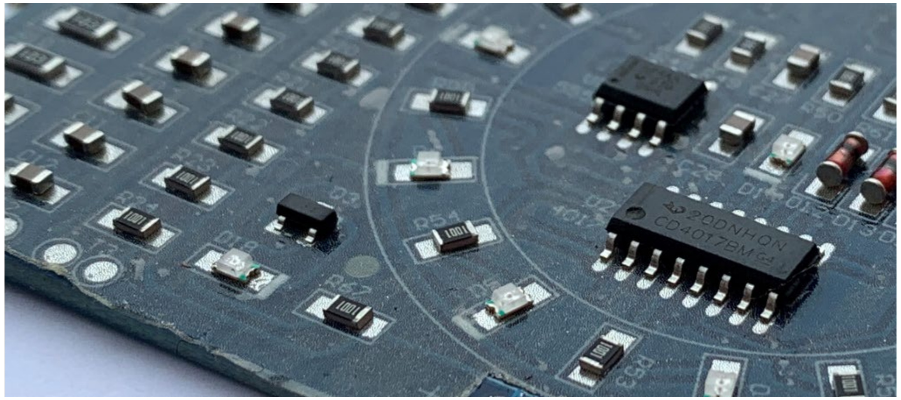


Figure 69: Anisotropic adhesive test with silver plated PCB

8.5 Final upgradeable PCBA concept

FPC connectors

Alternative to the anisotropic conductive tape: the FPC connector An FPC connector is commonly used to connect flexible substrates to rigid FR-4 PCBs (figure 70). Although using a connector will increase the modularity overhead of the upgraded component there are also a number of advantages:

- FPC connector provides precise alignment of the module
- The flexibility of the FPC connector is similar to the anisotropic film as the male connector part also does not require a propriety female connector design.
- Easy to use by layman users once the lever mechanism as illustrated in figure 71 is understood
- The connection is more robust
- The connection is reusable
- FPC connectors can have contact point on top (shown in figure 72) such that the complex wraparound design of the upgraded part is no longer required

The type of FPC connector s the back flip type with top contact.

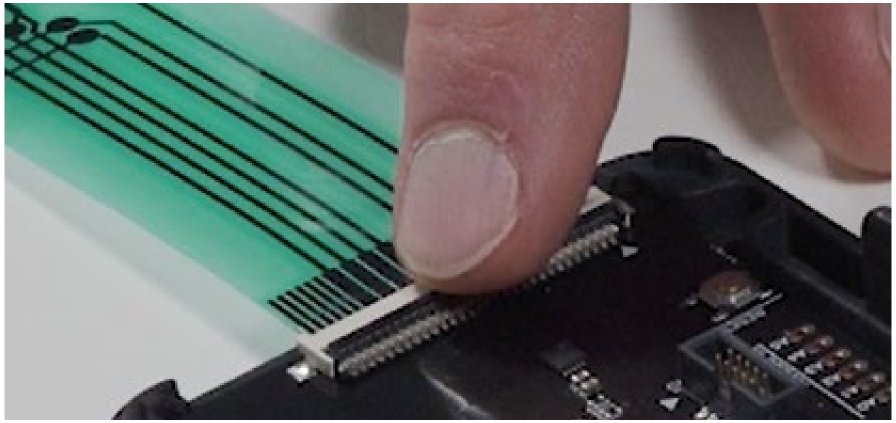


Figure 70: Traditional use of FPC connector

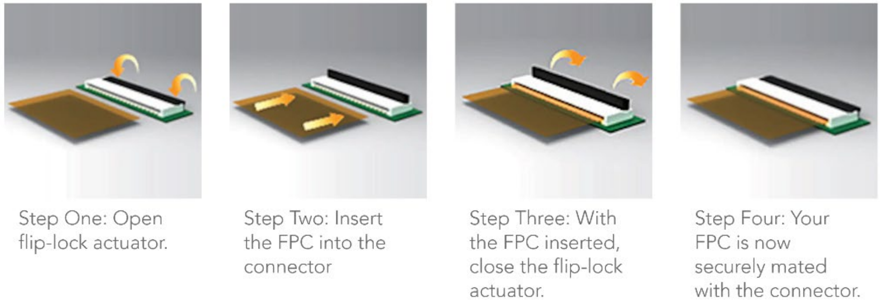


Figure 71: Operating principle of a back-flip FPC connector

Figure 72: Side view of top contact connector configuration

New layout of the modular PCBA

The new layout is presented in figure73 and includes the following elements:

1. **Antenna ground plane length** is maintained by the **diagonal antenna module** design and hereby ensures excellent antenna performance
2. **Connection point for the testing equipment** to test the status of the modules and components such that defect components can be identified and repaired and after reprocessing the PCBA can be checked before being given a new life.
3. **E-SIM chip** enables operator swapping without the need to physically swap the SIM card or place a new SIM chip
4. **Reserved module attachment space** (e.g. the LTE-M antenna clearance area) for new module attachment and support by the base plate
5. Contact pads for the **PV panel connector**
6. Contact pads for the **Battery connector**
7. New **Bluetooth LE antenna** allows for connection to external sensors
8. Baseplate design with **clearance area for enclosure encapsulation**

New attachment method options

One of the concerns was that the upgraded modules would start to vibrate, so an attachment method is necessary. Methods to attach the modules securely were mapped and presented in the following table.

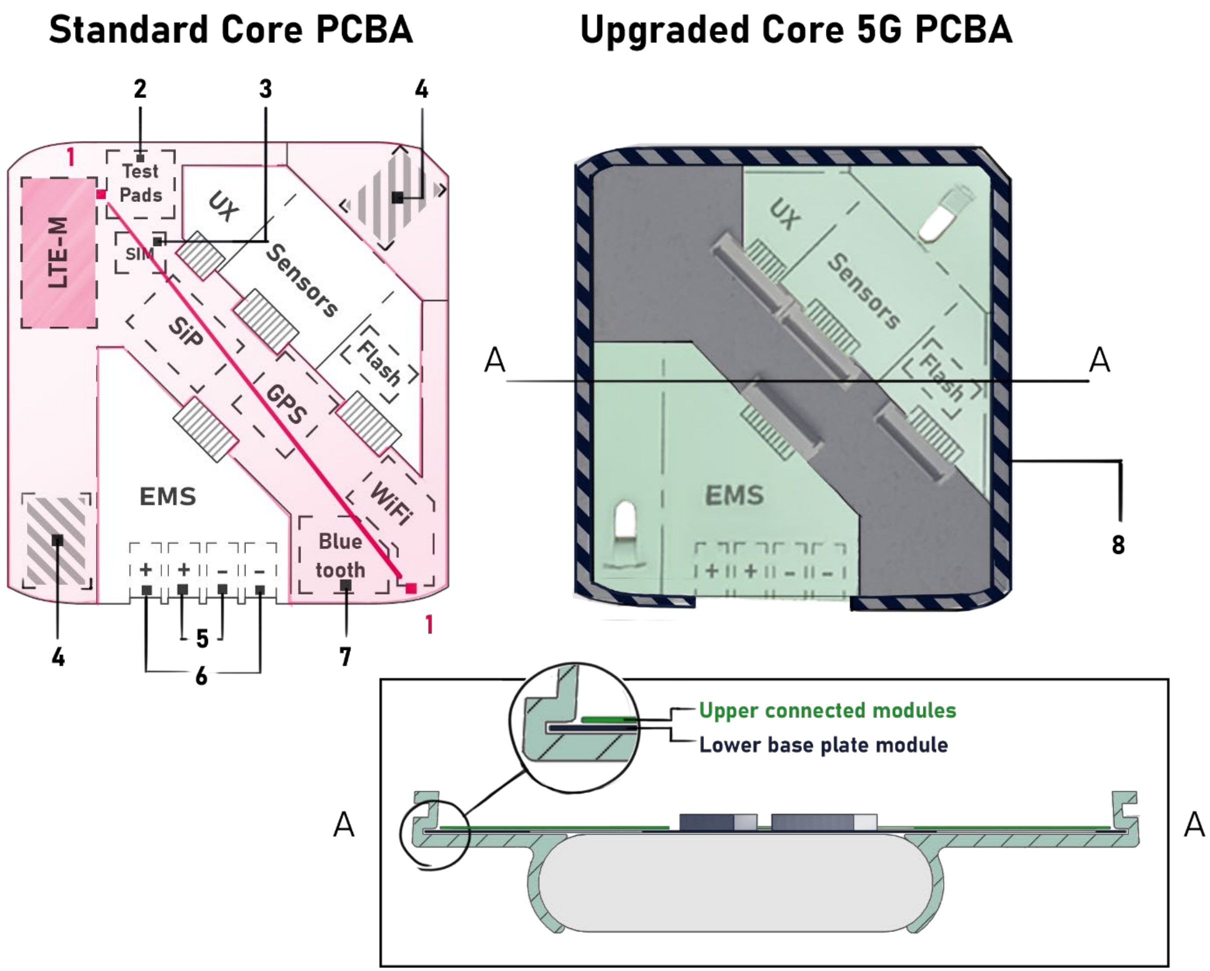
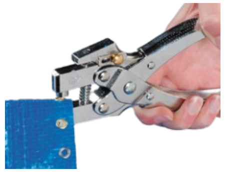
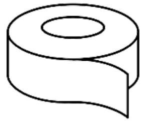


Figure 73: TRACK Core PCBA spatial (component) layout before and after upgrading

WISHES	MODULE ATTACHMENT OPTIONS				
	 **Folding connection**	 **Stapleless stapler**	 **Eyelet hole punch plier**	 **Adhesive tape**	 **Ultrasonic welding**
Minimal investment by SODAQ Manhours or tool cost	**++ No tool (pattern is precut)**	+ Inexpensive tool	+ Inexpensive tool	- Press and align tool	**-- Expensive equipment**
Compact dimensions Ability to ship the tool to the client	**++ No tool**	+ Compact tool	- Requires tool + eyelets	+ Requires compact tool	**-- Bulky equipment**
Precision of placement Tolerance of tool, risk of incorrect placement	- Precut pattern enables alignment, but tolerance of placement is high as connection can move	-- No alignment option	**++ Precut holes for eyelets**	-- No alignment option	-- No alignment option
Usability of tool Familiarity with tool, risk of incorrect use	- Easy to understand but folding requires good motor skills and small hands	**++ Very user friendly as most users are familiar with the concept of stapling**	+ Correct placement of eyelets may be challenging at first	+ Easy to use	- Practise is required to handle welding equipment
Reusability of connection Reversible connection	+ Folding back connection is relatively easy	+ Staple can be folded back	**-- Eyelets are very hard to liberate without damage to modules**	- Adhesives are generally not reusable	-- Weld is permanent
Recyclability Liberation of materials from substrate	++ Monomaterial	++ Monomaterial	**-- Eyelets remain in the substrate through encapsulation of the substrate**	**-- Adhesive leaves residue after removal contaminating the material**	++ Monomaterial
Attachment strength Chance of loosening of module	**-- Strength only if module is under tension**	+ Relatively strong	++ Very strong	+ Relatively strong	++ Extremely strong

Attachment method choice

The stapleless stapler came out best because the tool is very user friendly, has no negative impact on recyclability because the tool uses just the substrate for the attachment and the connection is reusable.

Final upgrade process steps

All new design choices come together in an updated upgrade process. All process steps are shown in the following images figure 74.

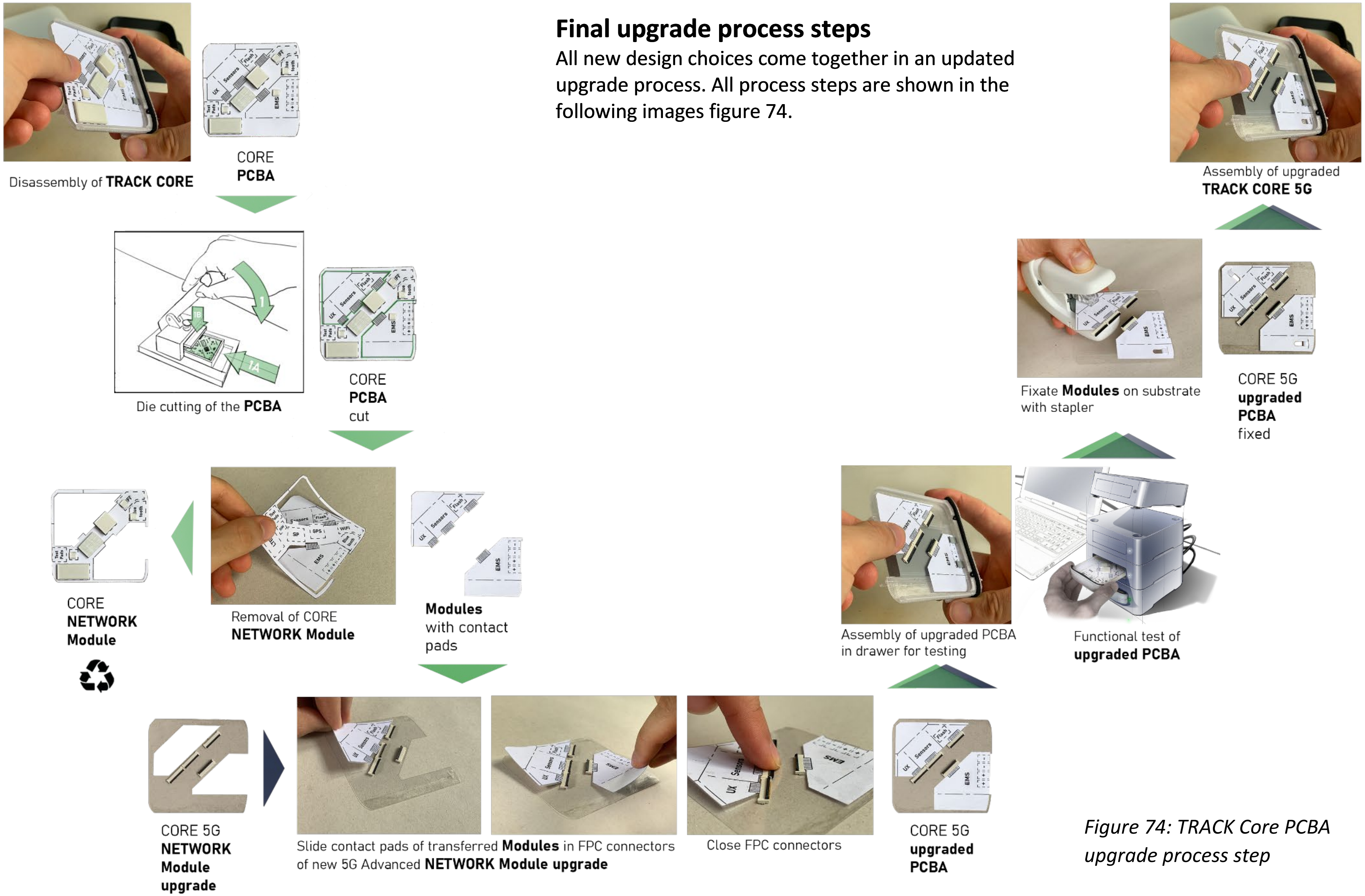


Figure 74: TRACK Core PCBA upgrade process step

8.6 Diagnostics equipment vision

Current diagnostics equipment
For the circular loops, diagnostics of the PCBA components health is required. To this end test pads are integrated into the PCBA layout. Currently test equipment is already used in the factory for QA after assembly of the PCBA. As these devices are custom made products they are expensive and not meant to be shipped to SODAQ.
Currently the SODAQ hardware engineers also have a way to connect external tools to the PCB using the two TAG-Connect ports for programming, debugging and for attachment of simple testing equipment (figure 75).

Stackable diagnostics box
In the diagnostics equipment vision, a similar type of spring-loaded connection method will be used, but more accessible to users outside of the hardware team. The user only needs to open the TRACK Core and remove the battery from the drawer and slide it into the diagnostics box like a cartridge. The box, shown in figure 76, will protect the PCBA during testing. It will house the testing pins and pins that connect to the PV and battery connectors.

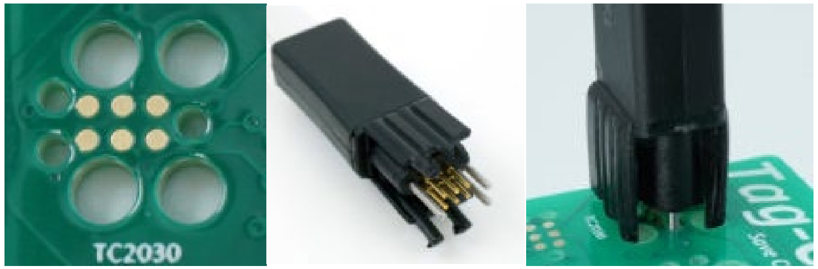


Figure 75: TAG-Connect port and spring-loaded connector used on the TRACK PCB

This way PV and battery run cycles can be simulated to see if these components are potential causes of the issue and no separate PV and battery diagnostics equipment might be needed.
The box is further designed to be stackable, such that more testing equipment can be added later on without taking up more space. Furthermore the equipment will be easy to detach from the stack to send the testing equipment to clients and facilitate the repairs or upgrades or resolve maintenance issues on-site.

Figure 76: Stackable test equipment vision with 'cartridge style' insertion option TRACK Core PCBA

9 VALIDATION

In the validation the most important requirements and wishes for the redesign of the TRACK from chapter 4 are verified.

9.1 Disassembly validation

Reduce the battery replacement time significantly

Disassembly time

The disassembly time and depth was determined using a video recording of the disassembly process using an electric drill for the screws.

TRACK SOLAR TARGET COMPONENT	STEPS [#]	TIME TO ACCESS [MIN]
PCBA	6	1:00
LIPO BATTERY	**7**	**1:20**
PV PANEL / TOP ENCLOSURE	9	> 8:00
SEAL / BOTTOM ENCLOSURE	8	1:00

TRACK CORE EXTERIOR MOUNT TARGET COMPONENT	STEPS [#]	TIME TO ACCESS [s]
PCBA	3	6
BATTERY/SUPERCAPACITOR	**3**	**6**
PV PANEL / MAIN ENCLOSURE	3	6
ENCLOSURE LIBERATION	9	20

TRACK CORE INTERIOR MOUNT TARGET COMPONENT	STEPS [#]	TIME TO ACCESS [s]
PCBA	4	17
BATTERY/SUPERCAPACITOR	**4**	**17**
PV PANEL / MAIN ENCLOSURE	4	17
ENCLOSURE LIBERATION	11	31

Enable disassembly of the PV panel

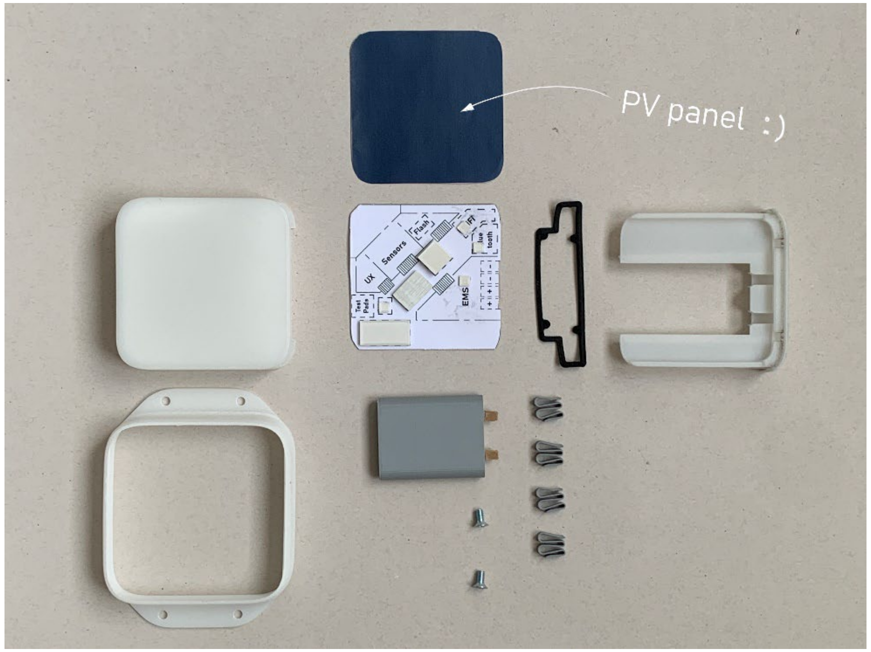


Figure 77: Component and fastener overview after complete disassembly (excluding interior mounting bracket)

Make connections reusable, no adhesives

All adhesive penalizations (X) are eliminated, also for the first dismounting step, in the disassembly map of the TRACK Core redesign in figure 78.

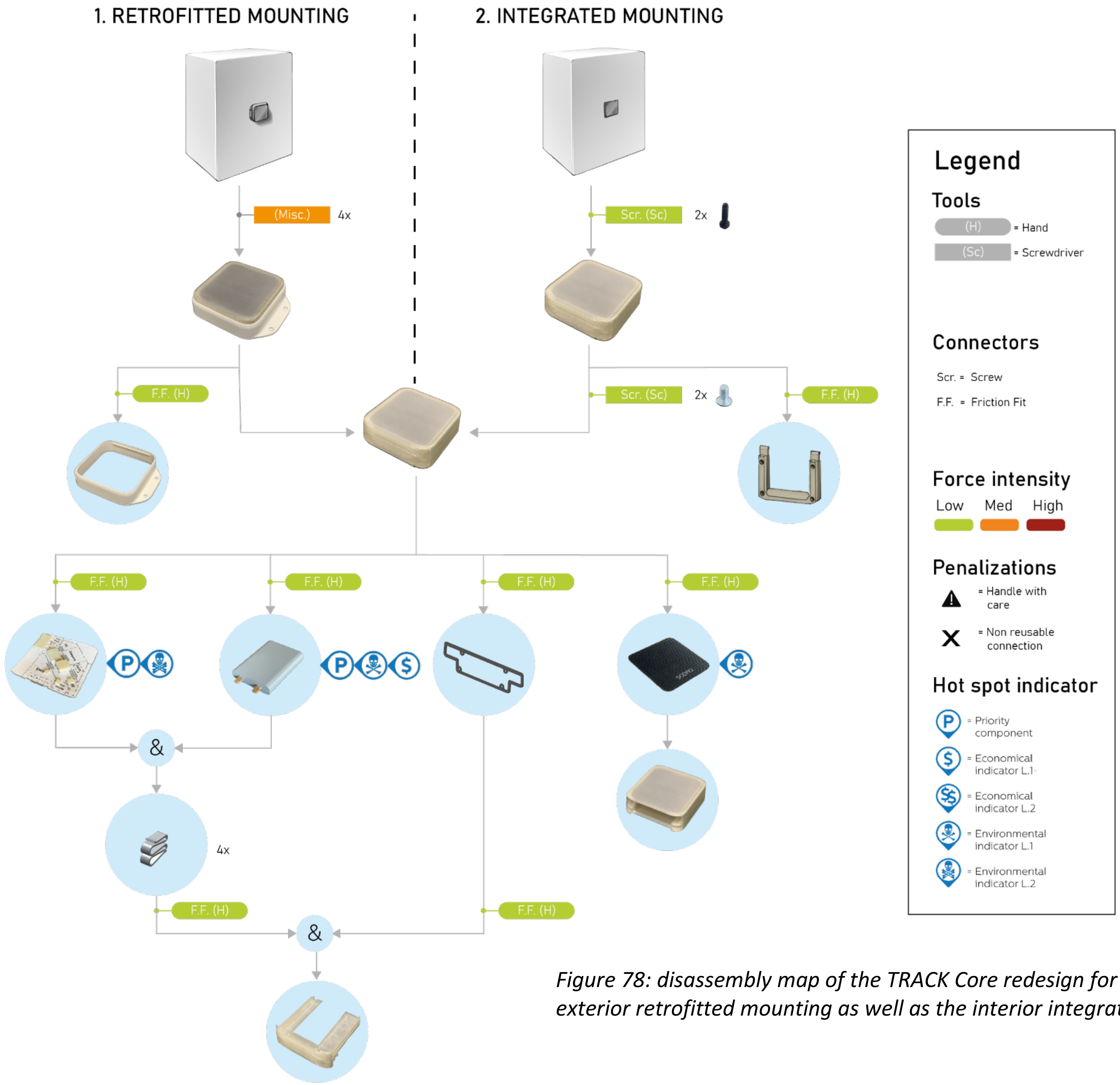


Figure 78: disassembly map of the TRACK Core redesign for both the exterior retrofitted mounting as well as the interior integrated mounting

9.2 Integration of world-friendly materials, components and new mounting options

✓	Integration of a modular, flexible PCB	SODAQ hardware engineers confirmed that technically the concept could work
✓	Excellent antenna performance	SODAQ antenna hardware engineers confirmed that with the new Core PCBA layout the current antenna requirements were met
✓	Provide the option to integrate (more flexible) emerging PV panels	With the new transparent enclosure flexible PV panels can be inserted easily and without the need for complex inner supporting structures that could have made the design of an IP67 rated product more challenging
✓	Integration of a Qi wireless charging coil	Qi charging is no longer necessary as the battery can be exchanged quickly
–	Design suitable for (Recycling Avenue) ABS injection moulding	Enclosure parts of final design is chosen to be transparent PC. Initially Recycling Avenue will not be able to provide this, but aims to offer PC in the future. Although Covestro Makrolon 2407 RE biobased PC was not selected due to the high virgin fraction, it could act as an alternative until solvent-based PC recycled input material becomes available.
✓	Design requires not more than three moulds	Design of the main enclosure needs to be injection moulded and the exterior or interior brackets can be 3D printed or injection moulded depending on production volume
✓	Integration into asset (mounting from the back)	Interior bracket in final design allows for asset integration without adhesives with only two mounting points
✓	Retrofitting onto existing assets using a bracket (mounting from the front)	Final design expands retrofitting opportunities and now also includes interior detachable mounting brackets

9.3 Sealing test

IP67 rating

IPX7 test with foam

The IPX7 test document with more detailed conclusions and illustrations is provided in appendix J1. These are the most important conclusions:

Sealing method variants

- The variant with **interior mounting bracket** was close the test but in the end did not pass the IPX7 test (half an hour under 1m water column) as some droplets were visible on the sides of the drawer (see figure 79)
- Unfortunately the enclosure prototype arrived warped, had been shrunken slightly and got deformed even further after tightening of the interior mounting screws.
  The deformations of the enclosure parts made that further testing with the **exterior bracket variant**, which relies on a good shape fit to work, was no longer informative.

Foam seal

- Two tests were performed. The seal with 1mm thickness in the first test could not be sufficiently compressed for sufficient sealing
- Using a seal of 2 mm thickness in the second test showed that this thickness should offer sufficient compression for the Core model tolerances in combination with a Shore hardness below 40B. However the geometry of the drawer would cause a gap where locally the compression was insufficient.

3D printed prototype enclosure

- SLS printed enclosure with vapor polish treatment seemed sufficiently watertight to be used for IPX7 testing. However, either the printing or finishing method in combination with the model geometry proved to be an unfortunate combination.

Figure 79: Droplets remain on the rail after removal of the drawer after the mounting variant underwent a IPX7 test

10. DISCUSSION

With the outcomes of the project known, the time has come to look forward. In the greater scope of things it has become clear that this project can only be considered the beginning of a complete shift to a more world-friendly product in a circular business mode. In this chapter the potential research directions are discussed to come to a closer the answer of a world-friendly tracking product.

10.1 Final prototype

IP67 rating as top priority

During the validation of the design goals for the world-friendly TRACK Core, the IP67 rating was one of the few goals that was not achieved in the final prototype. However as it is one of the key requirements, the rating ensures that the product can achieve a long life and given that water damage is the main failure mode of the current product, achieving the IP rating should be considered top priority during further development.

During the first IPX7 test several points for improvement were found for the variant with external mounting bracket:

- Tests should be performed with a more dimensionally stable design that includes design features that counter the warping. Only with a more accurate model the sealing concept could be validated
- Plastic deformation of the enclosure close to the mounting point after tightening the screw for the interior mounting variant is also a cause for concern. Although the stresses that cause the plastic deformation in the final product can become somewhat higher compared to the 3D printed prototype (yield strength of PC (Makrolon 2407 RE) is 66 MPa compared to 36-44 MPa for PA11).
- Measures to counter relaxation of exterior mounting bracket over time should be investigated. Relaxation of the bracket will impact the sealing performance which is of course undesirable.

The second IPX7 test shows that the variant with internal mounting bracket was close to achieving the rating, however a limited amount of water was able to enter after half an hour. After pinpointing the cause of the leakage the following recommendations for improvement can be given:

- The main leakage issue seems to be caused by the foam being pulled or pressed into the rail. The cause can be resolved relatively easily by decreasing the depth of rail as illustrated in figure 80.
- Foam with a lower shore value and deformation buffer room in the enclosure will help to seal more effectively.

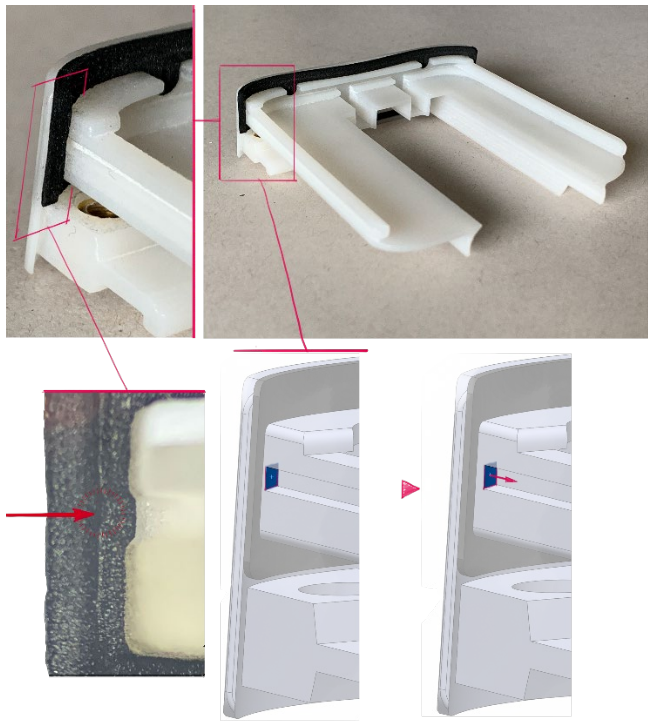


Figure 80: Redesign proposal of drawer rail cutout

Implications of transparent enclosure

The design choice to put the PV panel inside the transparent PC enclosure will influence the efficiency of the cells. Makrolon 2407 RE for example only has a luminous transmittance value of 88% (3mm wall thickness Covestro, 2021). It is also good to get an insight into the aging of a transparent enclosure and how this will affect the luminous transmittance over time.
Furthermore it is expected that condensation will form on top of the PV panel due to the humidity of the air trapped in the enclosure after the device is shut. Condensation issues generally can be solved by addition of a Gore vent, which works as illustrated in figure 81. Of course the assembly of the vent should be designed such that it can be easily removed from the enclosure (by hand) for better recycling of the enclosure or maintenance of the vent.

Lack of world-friendly appearance

With the choice for a transparent enclosure, the concessions have to be made regarding SODAQs' wish to use recycled materials and the recycled plastic aesthetic.
On the other hand will the choice for a biobased drop-in variant of PC lead to a significantly lower environmental impact as a result from low impact of the sourcing phase of the PC. The expectation is furthermore that the enclosure can be recycled using the solvent-based method from Recycling Avenue once the company has expanded their product range to PC. From then on Recycling Avenues recyclate can also become the source for future transparent PC TRACK Core enclosures.

User testing of disassembly, upgrading and diagnostics

While users, unfamiliar with the product architecture, have been observed while disassembling the product during the project, which led to some usability improvements, a structured assembly test has yet to be performed.

As most issues with the assembly and sealing seem largely solved, the moment has come to perform structured tests, including less tech-savvy users outside of SODAQ. This can reinforce the conclusion that the disassembly process has improved significantly, also for laymen users and will help to streamline the disassembly process further. Potentially labels or additional documentation are required as recommended by the guidelines from appendix D.
Furthermore the diagnostics equipment vision needs to be tested in validating the assumption about the concepts' ease of use.

Standardized diagnostics equipment

The main issue that has been identified by the hardware team is that testing equipment has a high cost of development.
In the future testing equipment cost can come down if the equipment will become more universal for SODAQ products. This means that a standard interface design will be necessary that works for a wider range of products, while speed and usability is kept in mind.

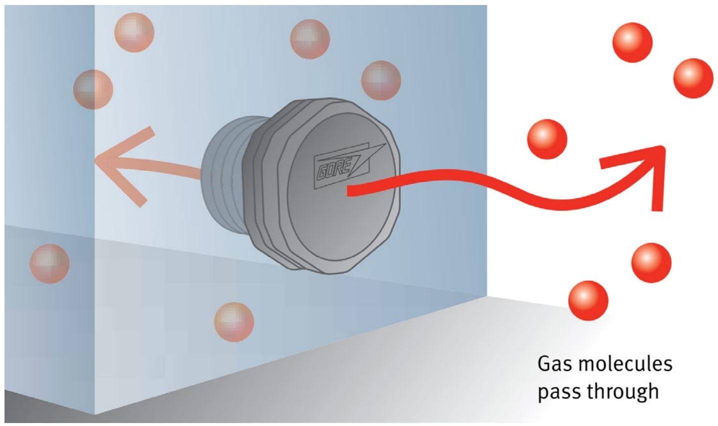


Figure 81: GORE protective vents reduce condensation because water vapor molecules can pass through the membrane. (Gore, 2016)

Unlocking the potential of asset integration

In order to show the potential of the new asset integration options, SODAQ needs to explore collaboration opportunities with the asset manufacturers of SODAQ's existing clients such as Buckhorn, the manufacturer of the seed containers.
These conversation will help SODAQ to understand how the TRACK Core (and the accompanying external sensors) can be integrated by design into assets for asset manufacturers to include 'intelligent' assets options in their product line up. An potential example is presented in figure 82.

Finally during the collaboration process the mounting options as proposed in this project can be further refined, with a continuous focus on decreasing the dismounting time such that it will be actually cost-effective to dismount TRACKs from assets.

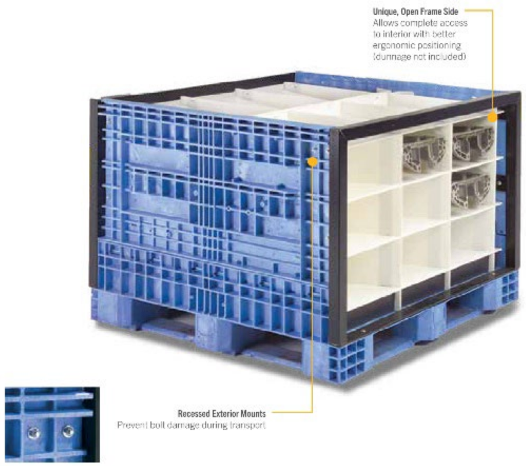


Figure 82: Buckhorn bulk container for safe transport of lightweight components and assemblies from supplier to final assembly points (Buckhorn, 2020)

More world-friendly materials

During this project for two of the three electronic components the world-friendly alternatives have been mapped. One major electrical component is left to be investigated: the battery.
The number of claims about more world-friendly or more efficient battery chemistries seems to grow every week. Due to the sheer number of options it was a market that was hard to understand and map out in terms of world-friendliness. Moreover, one of the goals was to eliminate the battery all together and thus was considered less important to investigate.
After it turned out that some form of energy storage would still be required as long as the most energy-intense process, the GPS positioning calculation, would not be replaced. It is therefore recommended going forward to study the world-friendliness of LiPo alternatives such as supercapacitors, solid-state, semi-solid-state or structural batteries.

Roadmap evaluation

In this report the future developments in terms of more world-friendly components, materials and production processes were analysed. Manufacturers were contacted, specification sheets were studied and webinars of market analysts were followed in order to get a better understanding of the state-of-the-art in each field.
Although the judgement of new technologies was done by using a lot of different sources, it is still possible that certain predictions might be off for specific real world condition. For example it might be interesting to find out how emerging PV panels behave for some use cases of the TRACK (e.g. luggage trolleys standing indoors) as these panels tend to have relatively high efficiencies in low light (indoors), and shading conditions. Or, due to the use of less metals in emerging PV panels there is less antenna interference that means that the surface area above the LTE-M antenna can be covered with active PV surface area as well. It can be those nuances that can actually make a difference and it is therefore recommended to continue to evaluate predictions in the roadmap.

10.2 Circular loops

In chapter 3 it was concluded that quick and easy disassembly of the product can be considered as an enabler of circularity of a product. With the embodiment concept at this stage meeting nearly all stated goals, the attention of the project can be shifted towards the practical implementation of the various loops, starting with reuse and (predictive) maintenance and preparing the PCBA for upgrading.

Business model

Implementing business model will prove to be a challenge that will no less complex than the making of an easy to disassemble product. Switching to a LaaS performance model as was suggested to profit fully from the ease of disassembly, proved very difficult to execute for a SME such as SODAQ in practise, due to the steep initial investment cost and risk associated with a completely re-engineered product.
One option would be to start off with a more linear classical sustainable business model and once the product has proven itself in the field, a select group of clients can be approached for a LaaS pilot project.

Market research circular product/service offering

Although the co-CEO expects that there will be market demand for reprocessed TRACKs, there is no hard evidence to back this up. Therefore it will be necessary to perform market research to investigate market demand for a circular location tracking service or a better serviceable products.

It is also important to find out what could tempt or reassure clients to consider adopting reprocessed products sooner next a more attractive price point.
Furthermore find out which clients are willing to participate in pilot project with a limited number of new enclosure designs and possibly designed such that current components can be used. So no upgradable, flexible PCBA, new connectors or a supercapacitor to keep investment cost reasonable for SODAQ.
This will also help to find out if clients want to take responsibility for the loops, as SODAQs co-CEO would like. This decision was already debated by the SODAQ design team as they found it difficult to imagine that users could be trusted to correctly execute the necessary reprocessing (e.g. upgrading of the PCBA) or testing steps.

Circular product journey

With this feedback in mind the following product journey overview, shown in figure 83 was made. The next step is to validate this product journey proposal with marketing, product manager of TRACK and customer service department and clients.
If approved, the practical implications for SODAQ in terms of necessary spare parts, tools and man hours for the case of an existing client can be mapped.
Cost calculations for the various circular strategies can then be performed to determine the ‘sustainability tax’ on the products price compared to the ‘unsustainable’ TRACK and on the other hand the potential cost savings per message due to life time extension

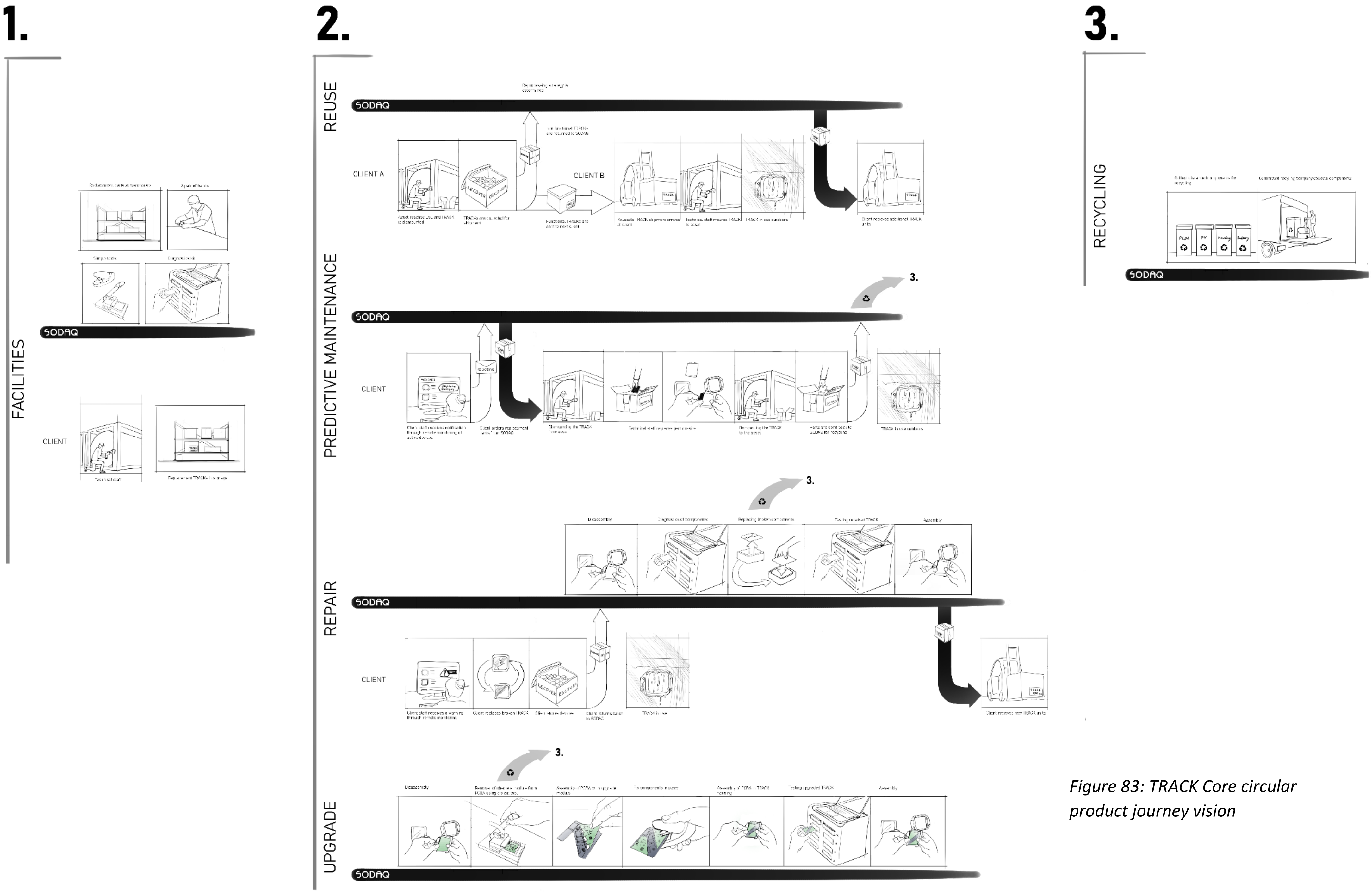


Figure 83: TRACK Core circular product journey vision

10.3 Data gathering

Conducting a full LCA

The variations in the 'Fast track' LCAs, proved that a Fast track LCA has limited added value in CO_2 reduction strategy for electronics Yes, they provide a very rough indication especially for the differences in impact between the electronics and the enclosure plastics, but a conclusive answer about relative contributions of the electronic components cannot be expected.

In this project choices for more world-friendly components were therefore based on comparative LCAs from literature and data about more sustainable production methods from companies, scientific literature and policy documents compared to the technologies used in the TRACK.

To provide a more definitive quantitative answer to the question about the contribution of new lower impact electronic components it is advised that SODAQ will perform a full LCA. In order to do this SODAQ will need to engage with their suppliers to obtain material passports, material declaration, CO_2e from internal LCAs.

Composition of a Product Passport & Recycler guide

Engaging with component suppliers will also help to collect information to create a Product Passport and a recycling guide, which are vital to achieve higher quality recycling of the components and the possibility to demand some financial compensation for the material recovery potential of defect electronic components.

A good example of such a guide is made for the iPhone by Apple. In the guide, of which a fragment is shown in figure 84, the target materials for recyclers of electronic components are clearly indicated.

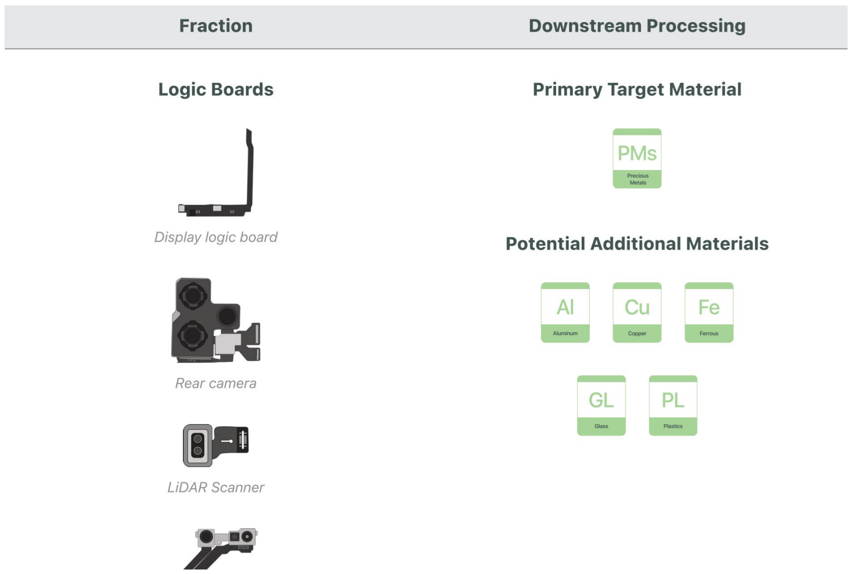
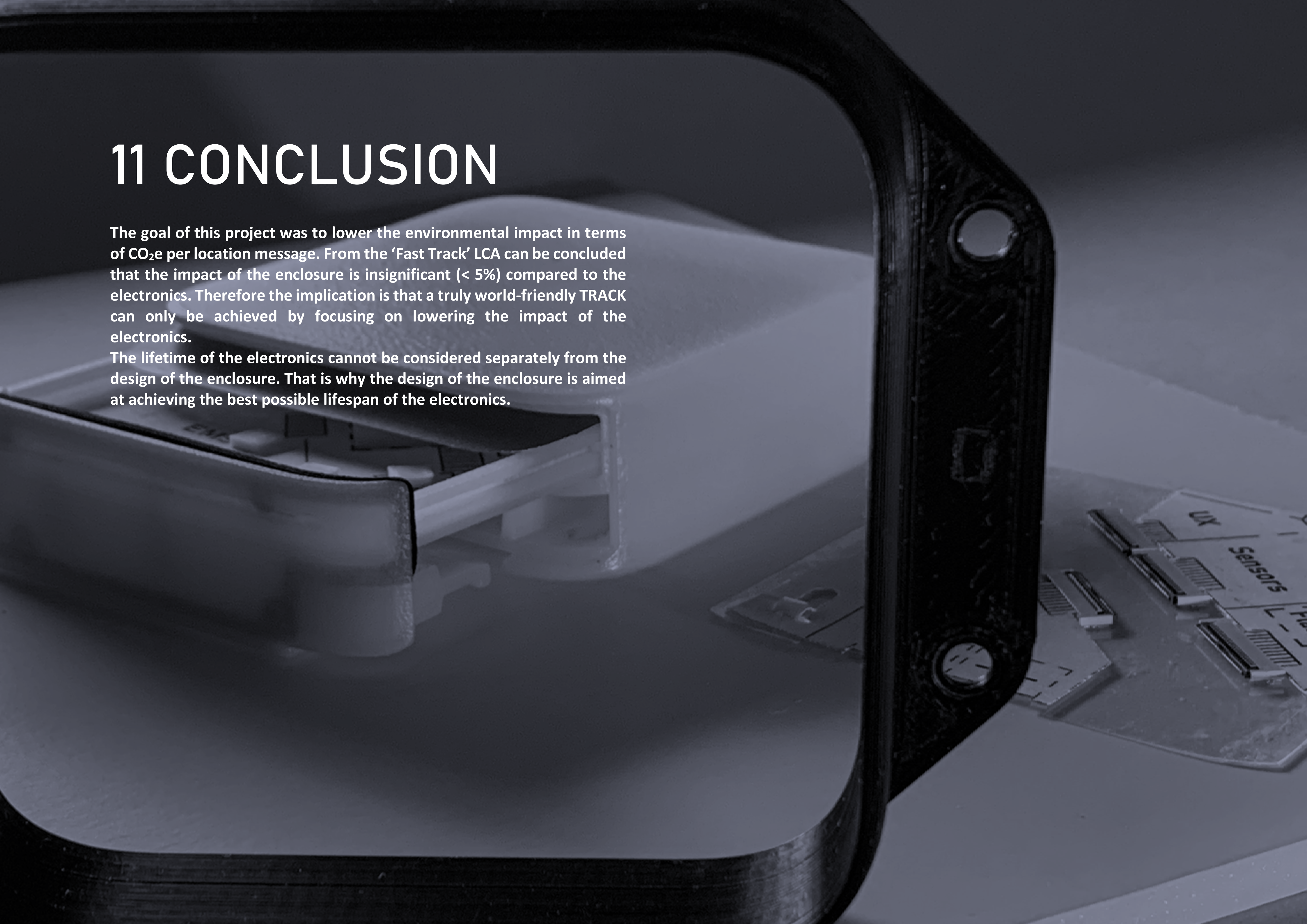


Figure 84: Apple Recycler Guide for iPhone 13 and 13 Max (Apple, 2022)

11 CONCLUSION

The goal of this project was to lower the environmental impact in terms of CO_2e per location message. From the 'Fast Track' LCA can be concluded that the impact of the enclosure is insignificant (< 5%) compared to the electronics. Therefore the implication is that a truly world-friendly TRACK can only be achieved by focusing on lowering the impact of the electronics.

The lifetime of the electronics cannot be considered separately from the design of the enclosure. That is why the design of the enclosure is aimed at achieving the best possible lifespan of the electronics.



There are two levers that can be pulled to lower the environmental impact of the TRACK:

1 lowering the initial impact of the sourcing and manufacturing stages of the electronics

- Electronics circuit printed on a recycled substrate made with 75%-86% less impact (for more sustainability benefits see section 5.2)
- Replacing the PV panel with a flexible emerging PV panel can lower panels 6 to 10 (for more sustainability benefits see section 5.3)

2 extending the lifetime of the electronics

hereby spreading the impact over a longer lifetime in which means more message can be send. This can not only be done by making a durable, weatherproof enclosure but also through the principles of circular product design.

- The enclosure is redesigned such that all components can be accessed and replaced directly after opening which resulted in disassembly times that can be measured in terms of minutes to one that can be measured in seconds.
- The PV panel is protected from weather influences by the transparent enclosure
- Furthermore the lifetime of the most impactful electronic components, the ICs, can be extended through a novel modular PCBA concept, in which modules can be replaced by removing the existing modules by cutting and attach new modules using a connector and stapling.
- This means that not only defect components can be repaired but also obsolete components such as the antenna, can be upgraded.
- By ensuring compatibility between generation of the TRACK it will be more attractive for SODAQ to keep spare parts in stock or to produce new spare parts for older generations efficiently.
- The battery can be replaced by a supercapacitor that can handle more discharge cycles and has less degradation due to extreme temperatures.
- By lowering the number of mounting point in the housing and by collaboration with asset manufacturers, dismounting the product from the asset will become more attractive for users for reuse or further reprocessing.
- The mounting bracket adaptable to new asset designs without changing the core enclosure

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13 APPENDIX

Appendix A1: Program of requirements

TRACK Solar general enclosure requirements

REQUIREMENT	UNIT/TEST
Environment	
Waterproof	IPX7 submersion (between 15cm and 1 m water for 30 minutes)
Dustproof	IP6X dust tight. (No ingress of dust for two to eight hours)
UV resistant	Aging test (Xenon arc test)
Protected against sea water corrosion	Aging test (Salt mist test)
Low water absorption rate	DIN 53495 (Change in mass of plastic)
Withstand temperature from -10C to +60C	Maximum expansion coefficient, test with air vent (Gore vent)
Use	
Vibration proof	din EN 60068-2-6
Shock resistant	Single drop from 1m high should not affect device performance
The mounting solution should protect against theft	
Lightweight	weight < 150 g

REQUIREMENT	UNIT/TEST
User interaction	
Transparency to guide light	Visual audio feedback at 1m from product
Transmissibility of sound waves	Hearable audio feedback at 1m from product
Electronics	
High transmissibility of radio waves around the clearance area of the antennas	
The product should operate autonomously for at least 5 years	Energy harvesting input power and energy storage capacity can cover the estimated energy consumption
Product needs to be fully charged before shipment to customer	
Aesthetics	
Product appearance matches brand identity	Brand identity guidelines
Products appearance blends in with asset (all black version)	
Production & assembly	
Ready for series production	10k units/year

Appendix A2: PCB component requirements

PCB COMPONENT	FUNCTION	REQUIREMENT
USB-C	Charging device before handover	USB opening in line with PCB
TEMPERATURE SENSOR	Monitoring temperature	Acceptable heat transfer
ACCELEROMETER	Wake-up	PCB connection free of vibration
3D MAGNETOMETER	Compass	N.A.
BAROMETER	N.A.	N.A.
LIGHT SENSOR	Detect dark environment	Transparent part
HALL EFFECT SENSOR	RESET	PCB positioned relatively close to top
2ND HALL EFFECT SENSOR	Anti-theft	PCB positioned relatively close to bottom
BUZZER	Audio feedback	Sound wave transfer
BUTTON	Send message manually	Flexible part
LEDS	Visual feedback	Transparent part
CONNECTORS	Connecting PV and battery to PCB	Fit + guide connectors

Appendix A3: PCB ground plane requirement

The antenna on the TRACK PCBs is implemented as quarter-wave (monopole) antennas on a flat conducting (copper) ground plane.

Ground plane length

The rule of thumb is that the ideal ground plane length is $\frac{\lambda}{4}$ with $\lambda = \frac{v}{f}$ with $v = 3 * 10^8$ m/s [speed of light] and f = 800 MHz [KPN LTE-M] provides an ideal ground plane length of $\frac{3*10^8}{8*10^8*4}$ = 94 mm

Ignion, the supplier of the LTE-M antenna recommends a ground plane length larger than 100 mm (Ignion, 2021) based on the measurements for an ideal evaluation board.

However, the SODAQ engineers decided go to go for a ground plane of around 70 mm (figure A2). This would be an ideal balance between size and energy consumption. To reach the required performance, the electronic design has to be tuned by SODAQs antenna hardware engineer.

B	$\eta_{a\ 824MHz}$
120mm	54.3
100mm	45.9
80mm	25.7
65mm	18.9
40mm	12.2

Figure A1: Antenna efficiency for different ground plane lengths B

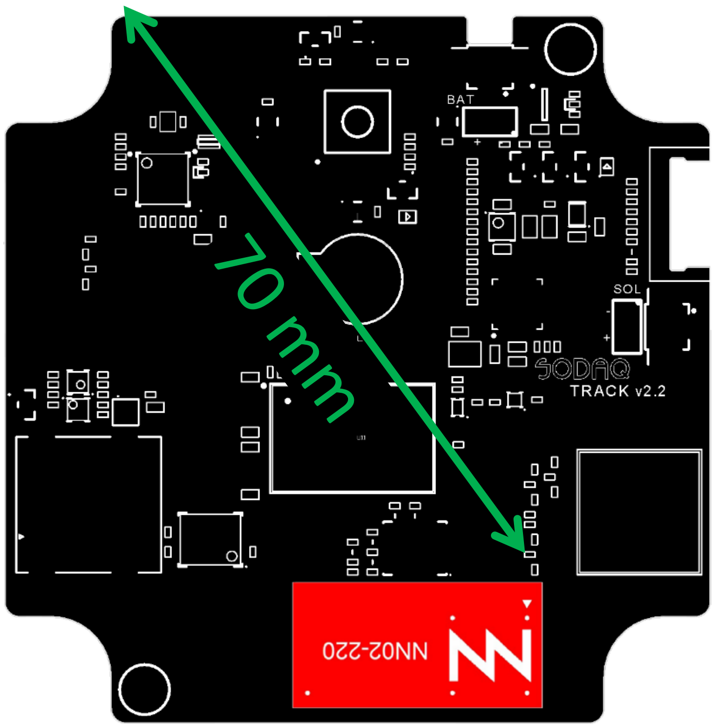


Figure A2: TRACK LTE-M ground plane length

Appendix B1: Existing impact analysis

From the start of the project there was reasonable doubt if the results provided by the externally conducted LCA study might be accurate. In general one would assume that the electronics would have a far more significant impact than the plastic housing, which could be as high as 70% of the total impact of the product according to SODAQs numbers.
So the initial assessment that by changing the housing material, the product will be much more 'world-friendly' might not be grounded properly. Therefore it was evident that the LCA structure and data should be studied in more detail to answer the question how the company got to this counterintuitive outcome.
Next to an external LCA, made by the company TraceLinq, there was a second internal LCA, performed by a former employee. To see if this would provide a more intuitive outcome, this LCA was studied first.

Internal LCA

For the internal LCA an Excel sheet for the different components was available. Unfortunately no description or references were added to check what software or database(s) were used to calculate the results. Furthermore the outcome of the LCA was shown in points rather than more common units such as 'kg CO_2equivalent' or 'Ecocost', so it remains unclear how to interpret and compare the results. As **SODAQ did not have sufficient confidence in the internal analysis**, no further effort was put in trying to get more information from the former employee.
However, it is still interesting to note that the outcome of the impact distribution chart from figure X, paints a completely different picture compared to SODAQs external LCA. In this analysis contribution of the enclosure is only 2%, while the majority (75%) comes from the PCBA.

TraceLinq LCA

In this case a lot more documentation was available, the information about applied method was very limited. After contacting Tracelinq for further explanation it turned out that the company was no longer in the business of performing LCAs. Luckily the software tool could be traced back by searching in which LCA software the large data format could be imported. This turned out to be OpenLCA, an opensource LCA tool.
After carefully reverse engineering the structure, while figuring out how the tool worked and what data was provided where, a couple of things started to surface.
First, although the presented structure for the LCA was very well done and quite complete, the translation step into the program is unfinished.
Second, the data that is put in does not seem to make much sense. For example, the only input material for the PCBA, a component known for its wide variety of materials, is steel rebar. This is a material is known for its use in the heavy construction industry and not for its use in the delicate electronic industry.

It is therefore not surprising that **the result and the conclusion of Tracelinq can be considered inaccurate.** After rerunning the analysis in the OpenLCA software the results show an input material source (PET) with a negative CO_2 impact. It remains unclear where the negative number comes from, but most likely it results from wrong input data of the battery. Moreover, diving in the structure the input for the battery shows High Density PE for the input instead of PET. It is correct that both materials can act as a separator material in a battery. However, this is a debatable material choice as it is unlikely that the polymer component in the battery would be the main contributor to the impact of the battery.

Appendix B2: LCA data

TRACK Solar Bill of Materials

COMPONENTS	COMPONENT MASS [G]	QUANTITY [#/PRODUCT]	MASS [G/PRODUCT]	MASS PERCENTAGE [%]	MAIN MATERIALS
BATTERY	40,8	1	40,8	27,7	LiCoO2, Al, C, Misc.
BOTTOM HOUSING WITH FLANGES	32,2	1	32,2	21,9	ABS/PC
TOP HOUSING SOLAR	28	1	28	19,0	ABS/PC
PCBA SOLAR	24,3	1	24,3	16,5	FR-4, Cu, Sn, Misc.
PV PANEL	13,9	1	13,9	9,4	EVA , ETFE, PV grade Silicon
ADHESIVE SOLAR PANEL	4,4	1	4,4	3,0	Acrylic
TORX SCREWS	0,4	4	1,6	1,1	Low carbon steel
SEAL	0,7	1	0,7	0,5	Rubber
ADHESIVE BATTERY	0,6	1	0,6	0,4	Acrylic
PCBA SCREWS	0,3	2	0,6	0,4	Stainless steel

Lithium ion battery footprint data

Database	Material	kg CO_2e/kg
Idemat 2022	LiCoO2 laptop battery (180 Wh/kg)	80,34
CES EcoAudit	Li-Ion, rechargeable (for laptops)	101,72
EcoInvent 3.7	Li-ion, rechargeable, prismatic	8,42
Fairphone 4 LCA*	Rechargeable lithium ion battery	25,12

*to obtain the conversion ratio kg CO_2e/kg, the provided CO_2e value (Proske, 2022) is divided by the Fairphone 4 battery weight

Appendix B3: Literature comparison

Unfortunately (publicly available) LCAs for comparable electronic products with a quantitative breakdown to component level turn out to be scarce. Still, a number of statements from LCAs for different electronic products could be extracted to form a conclusion:

"As a matter of fact, the PCB is always the most problematic item."

This study (Yung, 2011) provides a rather detailed life-cycle assessment of a battery powered outdoor temperature and humidity sensor. The first redesign recommendation for the company based on the findings is to reduce the size of the PCB.

"For more complex hardware profiles, ICs and PCB production are responsible for a significant part of the carbon footprint"

In this study, (Pirson, 2021) four IoT products were subject to a LCA. Of the four products the contribution of the casing was only visible for the most simple product (occupancy sensor).

"Motherboards can be the most energy intense components to manufacture."

Dell shared this insight in the press release of Concept Luna (Dell, 2021)., Dell's vision for a more circular laptop design, as it seemed to be one of the main focus points of the redesign. Among improvements in accessibility of the motherboard, the concept featured a 75% smaller, biobased PCB design housing with 20% fewer electronic components. According to Dell the redesign could halve the impact of the motherboard.

These statements all seem to support the conclusion that the PCB and in particular the integrated circuits (ICs) on the PCB are the main contributors to the CO_2 footprint of portable connected devices.

So for a final conclusive argument, let's take a closer look at the most extensive LCA that was found: the LCA of the Fairphone 4 (Proske, 2022), Fairphone's most recent phone.

As is visible in relative impact contribution of the components in figure B1, the results do indeed underscore the conclusion that the ICs cause the lion's share of the impact (74% in the case of the Fairphone 4).

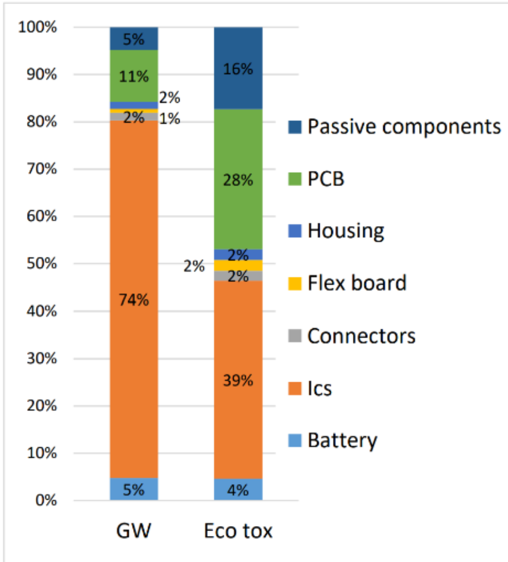


Figure B1: Relative impact of production per Fairphone 4 component

Additionally, Fairphone’s very detailed report shows two more things:

- A much lower contribution of the battery component of just 5% compared to LCAs of the TRACK (20-50%). The battery of the Fairphone 4 battery has 60% more capacity than the LiPo battery of the TRACK, but it is also around 60% heavier so one would expect that the material composition will be comparable.
  When putting Fairphone’s normalized battery impact number next to inputs from both databases used for the TRACK LCA, it becomes clear where the difference comes from: Fairphone’s impact estimate is about 70-75% lower per kg(see appendix B).
- The relatively high impact of the PCB production in terms of ecotoxicity. The Terrestrial ecotoxicty metric defines the impact the production of a component has on the natural environment and ecosystems. This excludes the impact on humans. It could be interesting to investigate the cause.

Appendix C: LCA in detail

PCBA

IC material sourcing
12 Pages of 55 entries (so around 660 entries) is the number of individual materials entries in the material declaration document of the main chipset of the TRACK. A snapshot of this list for one subcomponent is provided in appendix C4. And although there are duplicate materials among the entries, it symbolizes the sheer material composition complexity of some electronic components.

And of course all those different materials need to be sourced from different places. The primary source for the minerals will be mining (on land in open-pit mines, underground or even in the deep-sea). Unfortunately the activity of mining comes with the following negative external effects (IEA, 2021):

- The CO_2 footprint arising from the energy-intensive mining and on-site processing activities is significant.
- Environmental impacts, including biodiversity loss and social disruption due to land use change, water pollution depletion, waste related contamination such as mineral residues and air pollution from mine dust.
- Social impacts stemming from corruption and misuse of government resources, fatalities and injuries to workers and members of the public, human rights abuses including child labour and unequal impacts on women and girls.

After mining and on-site processing, the minerals are transported to different facilities for further refinement. Refinement of minerals can be an equally laborious and energy intensive process. For instance to achieve electronic grade silicon to create the silicon wafer, the basis of a chip, the silicon needs to be refined to a purity of 99.99999999% (10-11N) (Bernreuter, 2023). To achieve this the silicon has to go through several processing steps that require very high temperatures. For example during the Siemens Chemical Vapour Deposition process, silicon rods need to be heated to 1100°C for a couple of days to let the silicon grow to its desired size (Barron, 2022).

Likewise refinement of rare-earth elements (REEs) is very energy intensive, as separation of the elements is difficult due the similarity with other minerals in their atomic structure and the low concentrations in the ores (Talan, 2022).

Figure C1: PCB components overview

Nordic nRF9160 material declaration

Homogeneous Materials Summary

Subcomponent Description	Homogeneous Material Name	HM mass (mg)	Substance Name
Crystal	Base Au Plating	0.03000	Gold
			Thallium
	Base Ceramic	1.97000	Magnesium oxide
			Molybdenum Trioxide
			Manganese Oxide
			Aluminium oxide
			Quartz (SiO2)
	Base Metallization	0.38000	Molybdenum
	Base Ni-Co Plating	0.11000	Nickel
			Cobalt
	Cover Au Plating	0.00060	Gold
	Cover Brazing Metal	0.09160	Gold
			Tin
	Cover Ni Plating	0.06870	Nickel
	Evaporation Au	0.01700	Gold
	Evaporation Cr	0.00100	Chromium
	Cover - Kovar	0.67240	Iron
			Manganese
			Nickel
			Silicon
			Cobalt
	Electrconductive Adhesive	0.03835	Silver
			Silicon
	Epoxy Resin	0.18563	Silica, vitreous
			Trade Secret
			reaction product: bisphenol-A-(epichlorhydrin); epoxy resin
			Diglycidal Ether of Bisphenol A
			4,4'-BIS(2,3-EPOXYPROPOXY)-3,3',5,5'-TETRAMETHYLBIPHENYL
			Dibismuth trioxide
			Carbon black
	IC	0.12473	Silicon
			Aluminum
			Titanium
			Tungsten
			Arsenic
			Boron
			Copper
			Phosphorous
	IC Bump	0.00341	Gold
			Trade Secret
			Calcium
			Magnesium
			Iron
			Silver
			Copper
	Crystal	0.17700	Quartz (SiO2)

IC production

Currently there are 15 ICs present on the TRACK PCBA (figure C1).
As stated in the previous chapter, the Fairphone 4 LCA (Proske, 2022) and the literature (Pirson, 2022) showed that the production of all those ICs has a high impact in terms of CO_2.
ICs are manufactured using an extensive number of steps (1000+), which are complex, energy and chemically intensive, which are executed using extremely complex machines under extreme ‘zero dust’ environments (ASML, 2021).
Unfortunately it is hard to pinpoint the exact causes for the high environmental footprint of IC production as there seems to be a knowledge gap in this area (Ragnarsson, 2022). The ESG report of the fabless manufacturer of TRACKs main chipset also confirms this: “Data from suppliers is typically received as an average of their total emission by total production volumes and does not calculate for differences in the production unit (no. of wafer layers, size, and complexity of components). This leads to some uncertainties in the reported Scope 3 figures.” (Nordic Semiconductors, 2021). Figure C2 for example shows the effect of node size on electricity consumption.

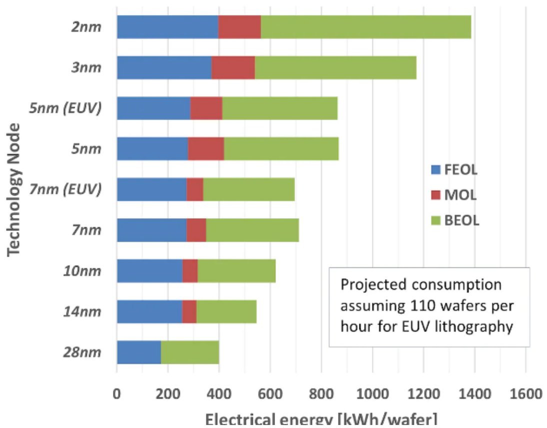


Figure C2: Electricity consumption per wafer node size

PCB production

PCB production on the other hand is less complex and the PCB construction is pretty standardized. This makes research into the sustainability aspects more accessible than for ICs.
Looking at the typical production steps of a four layer FR-4 PCB (figure C4-C6) there are a few steps raising concern. First of all PCB production creates a high amount of hazardous waste with the waste etching solution being the main source (see figure C3). Efforts are undertaken to recycle the copper as copper oxides from the waste water slurry and sold to smelters as this still has enough economic value (EPA, 2012).
A second point of concern are the energy intensive PCB lamination steps. During lamination the etched copper layers and FR-4 layers are assembled together using a large lamination press. The layers are first exposed to a vacuum after which a very high pressure is applied. When under pressure, the layers are heated up to high temperatures to cure the resin in the prepreg and merge the layers together (Knack, 2021).

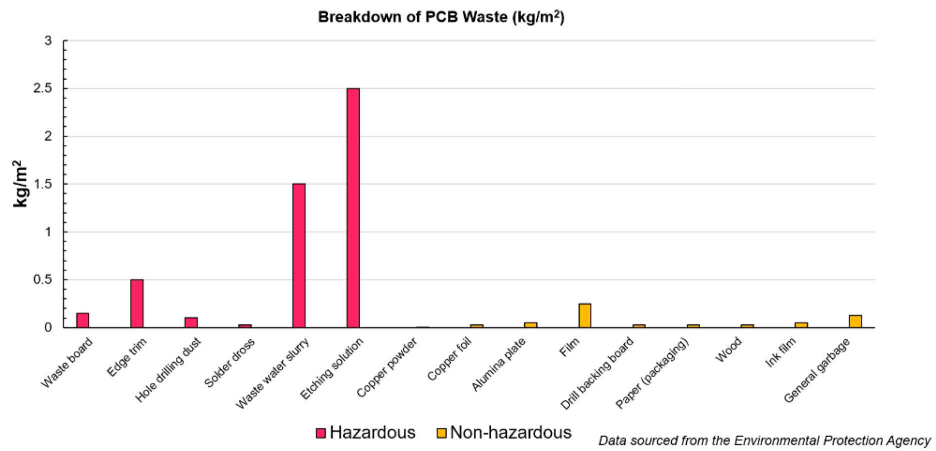


Figure C3: Breakdown of PCB production waste (IDTechEx, 2022)

PCB production process

Sources: (MCL,2023), (MKTPCB, 2023), (AEE INTEC, 2016)

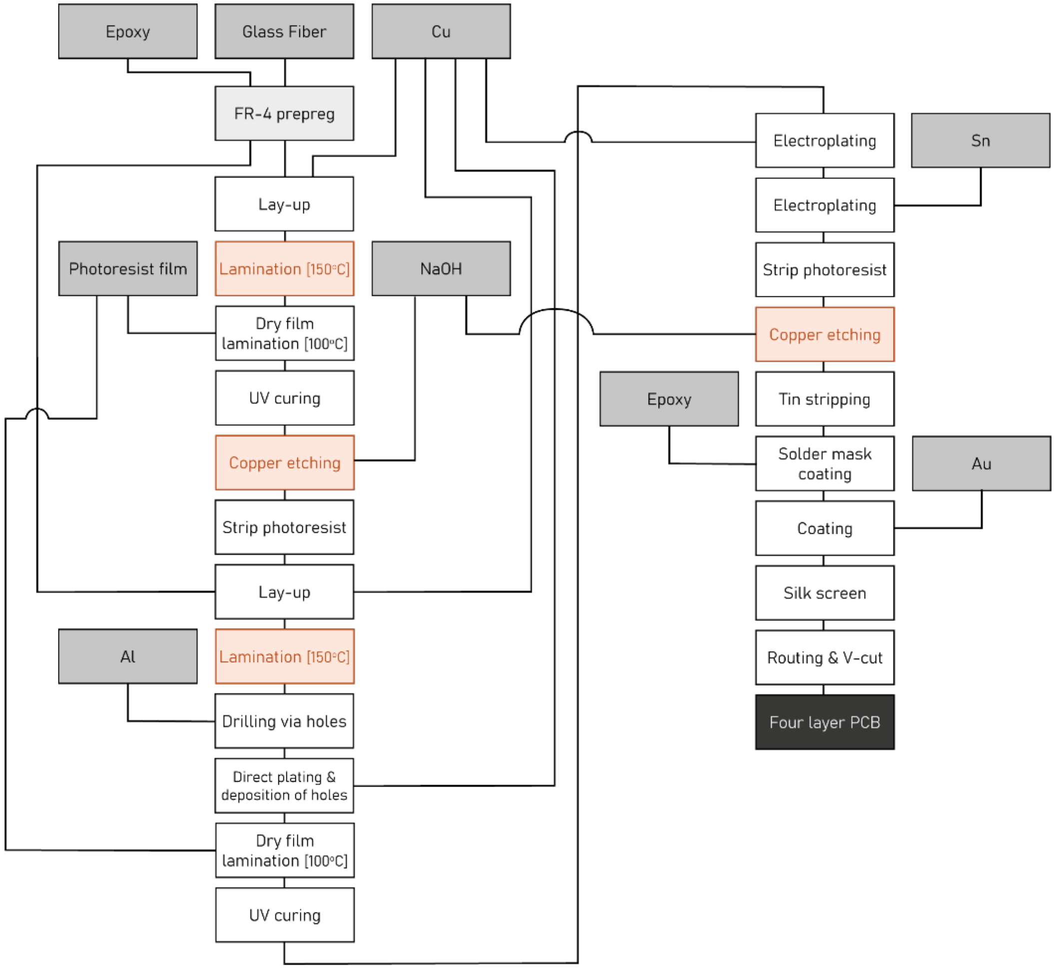


Figure C4: TRACK four layer PCB FR-4 production process

Figure C5: TRACK 'four layer' PCB stack

Figure C6: Typical lay-up of four layer PCB

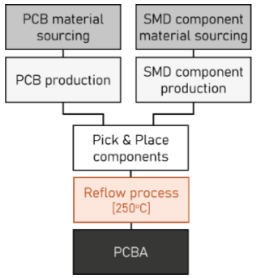


Figure C6: SMD components production

PCBA assembly

After production of the PCB and the electric components or Surface Mount Devices (SMD) follows the assembly, the so-called reflow soldering process. For the applied solder paste to flow and adhere to the contact pads on the board and the SMD components, the PCB has to go through a high temperature reflow oven for a couple of minutes (figure C6). This makes it an energy intensive process step.

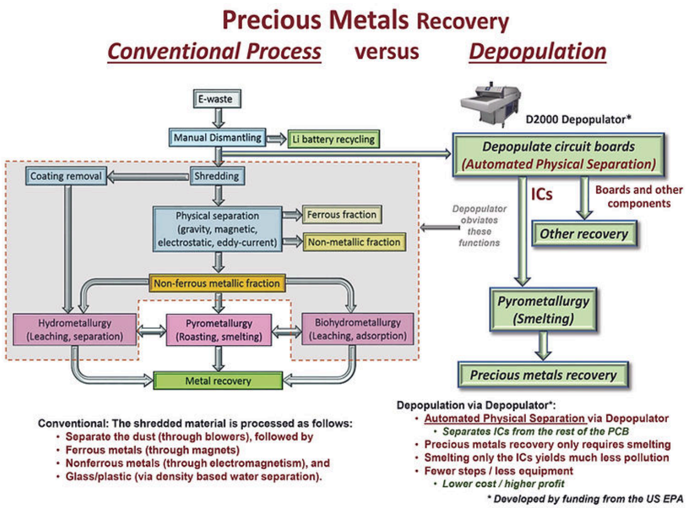


Figure C7: PCBA recycling processes (Advanced Recovery & Recycling, 2023)

PCBA recycling

Given the fact PCBAs generally contain substantial quantities of precious metals and in concentrations significantly higher than those found in ores (Cayumil, 2017), it would make sense to recycle them with high quality (i.e. the urban mining concept). However in practise this is rarely the case; only half of the Waste Electrical and Electronic Equipment (WEEE) is recycled compliantly in the Netherlands (Balde, 2020), if it gets collected in the first place of course. And even if an end-of-life TRACK product would end up at the recycling facility, theoretical recycling percentages for precious metals are still very low. Fairphone estimates that around 20% of the metal fraction (by weight) could be recovered in a best case scenario of dismantling and selective smelting (Reuter, 2017).

Barriers to further development of recycling of PCBs and secondary supply of REEs and precious metals include (CEWASTE, 2021):

- Competition from primary supply with prices that often do not account for the negative external effects.
- Difficulty in accessing the components due to the design of products, their miniaturisation and increasingly complex material mixtures in WEEE.
- Knowledge gap of where specific materials are actually concentrated and a lack of (detailed, quantitative) information and marking of the key components and their chemical composition.
- No clear requirements to recycle the materials, the generic, weight-based collection and recycling targets for WEEE in the EU has led producers and member states to focus on quantity instead of high-quality recycling of the small amounts of REEs and precious metals in products. These targets makes the recovery of 1 kg of concrete from a counterweight from a washing machine equally important as recovering 1 kg of gold from a PCB (Hagelüken, 2006)

Next to the metal fraction PCB also consist of a large non-metal fraction, the FR-4 material is a glass fibre epoxy composite. Typically composites are not recycled, as the materials are of such a deteriorated quality after recycling that it is not economically viable to do so (Joustra, 2021).

PV panel

Silicon sourcing

Although solar energy might be considered an emission free source of electrical energy, this is unfortunately not true for its production. This has led critics of clean energy (Moore, 2020) to highlight the fact that fossil sources are still being used to create renewable energy sources and vast amounts of high purity quartzite have to be mined. This including the negative effects associated with mining activities (see IC material sourcing).

It is indeed true that coal cokes are used in the process to reach the extremely high temperatures (> 1900 °C) necessary for the refinement of the silicon to a metallurgical grade (99% or 2N pure silicon) (Satpathy, 2020). Although further refinement to PV grade (9-10N) is somewhat below electrical grade silicon (10-11N) the refinement steps are similar and mapped out in figure C9.

After the treatment in the submerged arc furnace and the Siemens process (as discussed for electrical grade silicon), a third silicon refinement step, the Czochralski process that grows a silicon ingot, consumes vast amounts of energy (Bernreuter, 2023). As 97% of the wafer production is concentrated in China (IEA, 2023), the required electricity comes from the Chinese coal dominated grid; a 60% share in the electricity mix in 2020 (IEA, 2023).

Next to the extremely high energy demand, the refinement process can result in the leaking of hazardous chemicals such as extremely toxic silicon tetrachloride, which is the input material for the Siemens process, or sulphur hexafluoride. This chemical is used to clean the reactors and when released into the atmosphere it acts as a 22,000 times more potent greenhouse gas than CO_2 (Landrat, 2018).

PV cell and module production

The sourcing stages result in a silicon wafer, the basis for the production of the monocrystalline solar cell.
Regarding the production of the cell, the main steps raising concern are the diffusion of a phosphorus layer, which is the most common way to form the (electron) emitter layer; the negative terminal of the solar cell (Solar Magazine, 2022). The application of an antireflective coating through chemical vapour deposition (Hoex, 2023) and finally the high temperature process that fires the front and rear contacts onto the cells (Hoex, 2023).
In addition to the high energy demand, many chemicals are used in this manufacturing process, for example texturizing of the silicon wafer by etching with hazardous chemicals such as sodium hydroxide or potassium hydroxide (Stapf, 2019).

Monocrystalline PV panel production process

Sources: (Bernreuter, 2023), (SMC, 2023), (Jinko Solar, 2021), (Hoex, 2023)

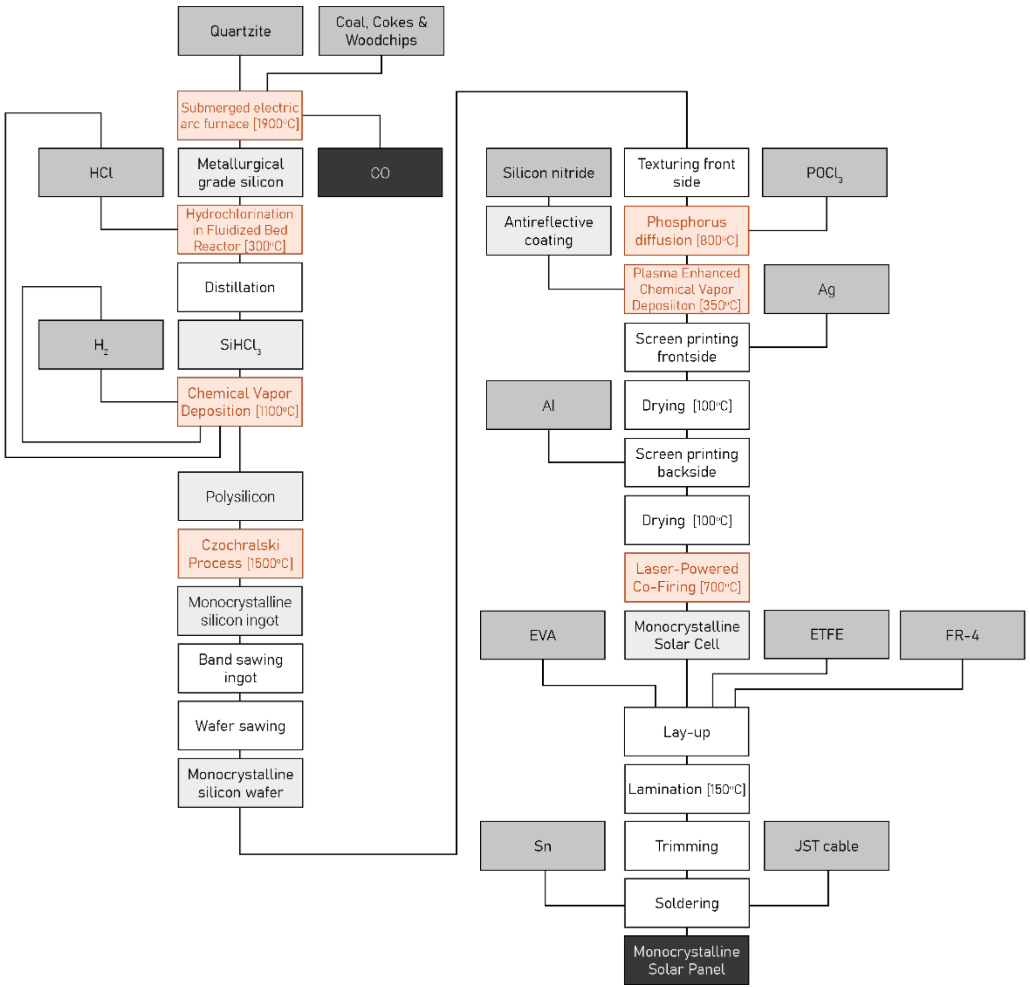


Figure C8: TRACK monocrystalline Si PV panel production process

Figure C9: Specifications of TRACK monocrystalline PV panel

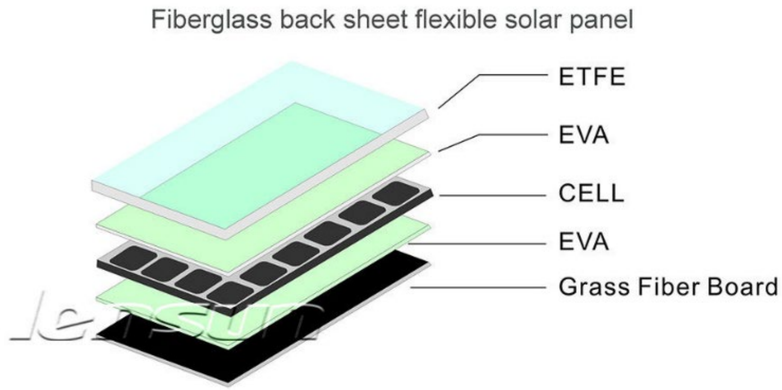


Figure C10: Lay-up structure of TRACK monocrystalline PV panel

PV panel recycling

Currently, when PV modules reach end-of-life most 'recycling' happens through glass or metal recycling facilities. These facilities can only recover bulk materials such as the aluminium frame, junction boxes with electronics, copper cables and often the glass plate. Although these materials account for 90% of the total mass of a module (M2i, 2021), recovering the small percentage of other elements such as silver, copper, silicon and lead, is not considered profitable. While these elements not only have the highest potential value, they also cause the highest environmental impact, especially if not handled correctly (lead and PFAS) (Heath, 2020). Manufacturers have designed PV modules to be reliable for 3 decades or more and these robust designs make liberation of materials extremely challenging. One of the main issues that prohibits dismantling is the EVA (ethylene vinyl acetate) encapsulant applied on the front and back side of the cells (see figure C10). Because the cells and EVA are laminated in a vacuum (much like PCBs), the encapsulant is physically inseparable from the cell. This means most of these valuable metals are now lost after shredding the panels and end up as a filler material for concrete or as a sub base for roads (Späth, 2022).

However, the recycling technology to extract these elements does exist (see figure C11), albeit only in France (Veolia, 2022) and on pilot scale in some EU countries (Fraunhofer ISE, 2022). Without government subsidies or higher producer fees (Stichting OPEN, 2022) and the security regarding available quantities, further necessary investments in new recycling plants are not considered probable in the near future (Deutsche Umwelthilfe, 2021), (Späth, 2022).

Figure C11: PV recycling process by Veolia

LiPo battery

Material sourcing

The TRACK LiPo battery consist of several main components: a cathode consisting of a mix of lithium and cobalt, an anode mainly consisting of graphite, a separator polymer (in this case polyethylene) and an aluminium casing. The minerals lithium and cobalt are considered to have the highest environmental impact in LiPo batteries, however the impact of battery-grade graphite can be as much as 4 (Engels, 2022) to potentially 10 (Mining.com, 2023) times higher than the values found in current LCA databases.

Lithium

The largest supplier of lithium is Australia (see figure C12) where the mineral is mined from hardrock in open pit mines, while in Chile, Argentina, Bolivia (lithium triangle) and China lithium is extracted from brine out of so-called salars (salt deserts). In some areas near these salars, locals complain about increasing droughts. Studies are suggesting that the water stress is directly related to the extraction of lithium from the underground salt water lakes (Liu, 2019).
While lithium demand has been growing rapidly over the last years, the additional supply mainly comes from hardrock based mining. Unfortunately the CO_2 impact of lithium from hardrock is estimated to be three times higher (per kg) than from brine (IEA, 2021).

Cobalt

The main source of cobalt is the Democratic Republic Congo (see figure C12), where cobalt mining is associated with unstable artisanal and small-scale underground mines, generally without access to safety equipment. (Murray, 2022), (The Impact Facility, 2021). Furthermore children have been found to be present at about 30% of cobalt artisanal mine sites in the DRC (IEA, 2021).

$LiCoO_2$

After the mining, lithium and cobalt have to go through several refinement steps until they can form the lithium cobalt oxide ($LiCoO_2$) cathode material through calcining the mixture of both minerals at temperatures up to 850°C for 5 to 10 hours (Japan Patentnr. EP0867408A1, 1998).

Graphite

Graphite is a fossil carbon which is either mined or made from other fossil-based materials. Refinement to anode grade graphite is particularly energy-intensive and situates in regions with low-cost energy, such as Inner Mongolia and regions in China where the grid is dominated by coal and therefore has a high CO_2 footprint.
But also a large part of the production steps, especially the most energy intensive steps such as the carbonization of the coating of the graphite particles in an electrically heated furnace at 1300°C for 15h are not taken into account (Engels, 2022).
Furthermore for sourcing of graphite toxic chemicals such as sodium hydroxide and hydrofluoric acid are used with their associated environmental concerns when disposed in an unregulated way.

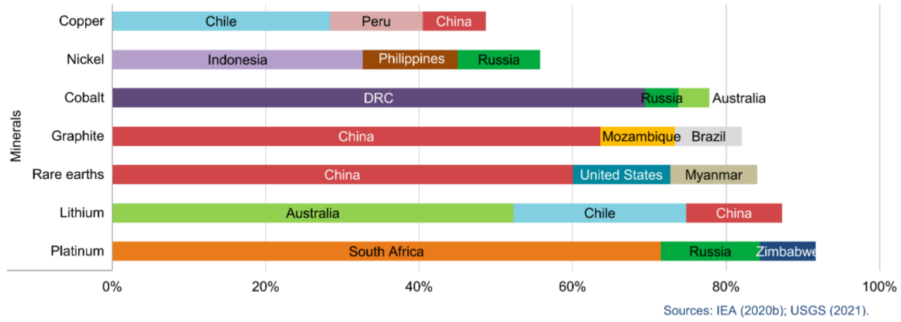
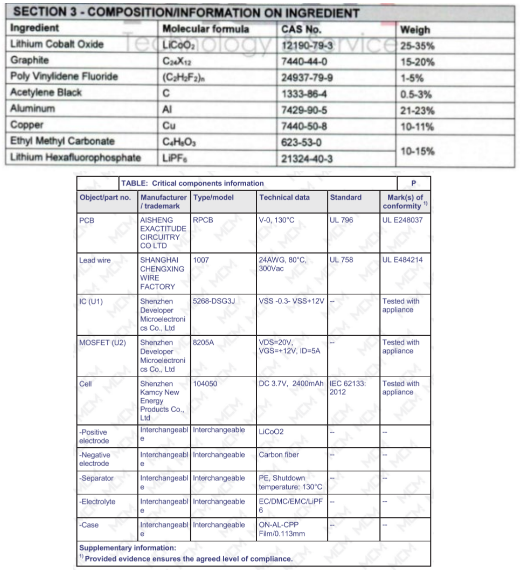


Figure C12: Share of top three producing countries in total production for minerals (IEA, 2021)

C7: LiPo battery production process

Sources: (Targray, 2023), (Tmax Battery Equipments, 2023), (Cambridge Energy Solutions, 2023)



SECTION 3 - COMPOSITION/INFORMATION ON INGREDIENT			
Ingredient	Molecular formula	CAS No.	Weigh
Lithium Cobalt Oxide	$LiCoO_2$	12190-79-3	25-35%
Graphite	$C_{24}X_{12}$	7440-44-0	15-20%
Poly Vinylidene Fluoride	$(C_2H_2F_2)_n$	24937-79-9	1-5%
Acetylene Black	C	1333-86-4	0.5-3%
Aluminum	Al	7429-90-5	21-23%
Copper	Cu	7440-50-8	10-11%
Ethyl Methyl Carbonate	$C_4H_8O_3$	623-53-0	10-15%
Lithium Hexafluorophosphate	$LiPF_6$	21324-40-3	

	TABLE: Critical components information				P
Object/part no.	Manufacturer / trademark	Type/model	Technical data	Standard	Mark(s) of conformity [1)]
PCB	AISHENG EXACTITUDE CIRCUITRY CO LTD	RPCB	V-0, 130°C	UL 796	UL E248037
Lead wire	SHANGHAI CHENGXING WIRE FACTORY	1007	24AWG, 80°C, 300Vac	UL 758	UL E484214
IC (U1)	Shenzhen Developer Microelectronics Co., Ltd	5268-DSG3J	VSS -0.3- VSS+12V	--	Tested with appliance
MOSFET (U2)	Shenzhen Developer Microelectronics Co., Ltd	8205A	VDS=20V, VGS=+12V, ID=5A	--	Tested with appliance
Cell	Shenzhen Kamcy New Energy Products Co., Ltd	104050	DC 3.7V, 2400mAh	IEC 62133: 2012	Tested with appliance
-Positive electrode	Interchangeable	Interchangeable	LiCoO2	--	--
-Negative electrode	Interchangeable	Interchangeable	Carbon fiber	--	--
-Separator	Interchangeable	Interchangeable	PE, Shutdown temperature: 130°C	--	--
-Electrolyte	Interchangeable	Interchangeable	EC/DMC/EMC/LiPF6	--	--
-Case	Interchangeable	Interchangeable	ON-AL-CPP Film/0.113mm	--	--

Supplementary information:
[1)] Provided evidence ensures the agreed level of compliance.

Figure C13: Composition of TRACK LiPo battery

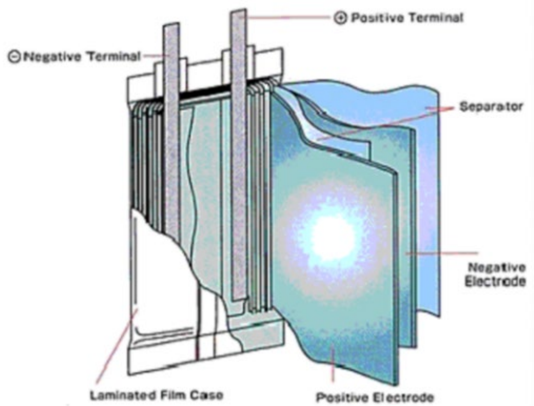


Figure C14: Structure of a typical LiPo pouch cell

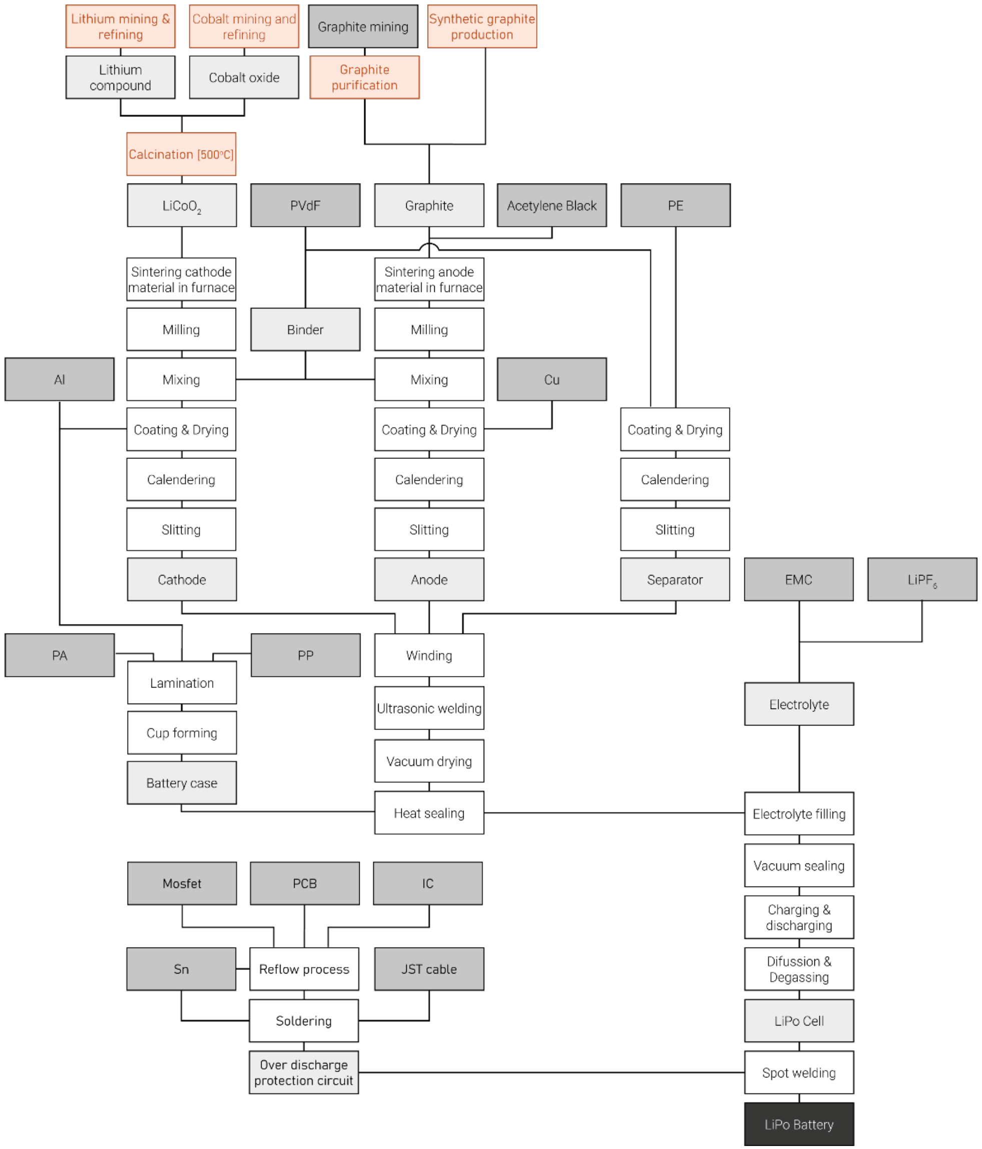


Figure C15: TRACK LiPo Pouch cell production process

Battery recycling

Due to the apparent abundance of lithium in nature, recycling of the mineral was not considered a priority for the lithium-ion battery, glass and ceramics industry. This shows: at the moment less than 1% of lithium is recovered at EoL (see figure C16).

The recent increase in demand for lithium for electric vehicles has shifted this view and emphasized the importance of recycling (Umicore, 2023). This poses the lithium-ion battery recycling industry for several challenges (IEA, 2021):

- Batteries are not removed from appliances and end up in e.g. metal recycling together with WEEE.
- There is a variety of different battery designs requiring specific and different logistics approaches.
- The infrastructure to transport and store the growing number of waste batteries is lacking as measures to reduce safety risks of a "thermal runaway" during logistics and reprocessing are expensive.
- A lack of efficient battery recycling technologies and large-scale recycling capacities in Europe.
- Competition from primary supply with prices that often do not account for the negative external effects.

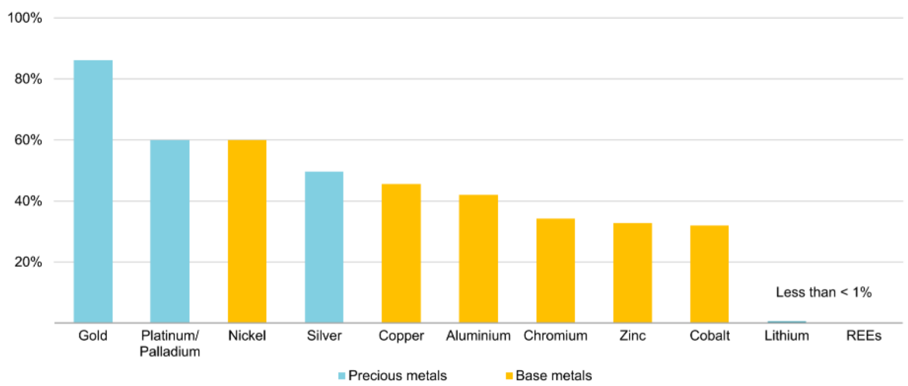


Figure C16: Global metal EoL recycling percentages in 2021

Currently the most established recycling method for lithium-ion batteries consists of smelting at high temperatures to recover an alloy of valuable metals, like cobalt and copper which is then be further refined (figure C17). The major downside of this (pyrometallurgical) process is the fact that the graphite is lost completely through incineration and the lithium component ends up in the slag. While the slag could undergo (hydrometallurgical) lithium recovery, currently this option is not yet considered economically attractive and the slag is sold as an additive for construction materials (Latini, 2022).

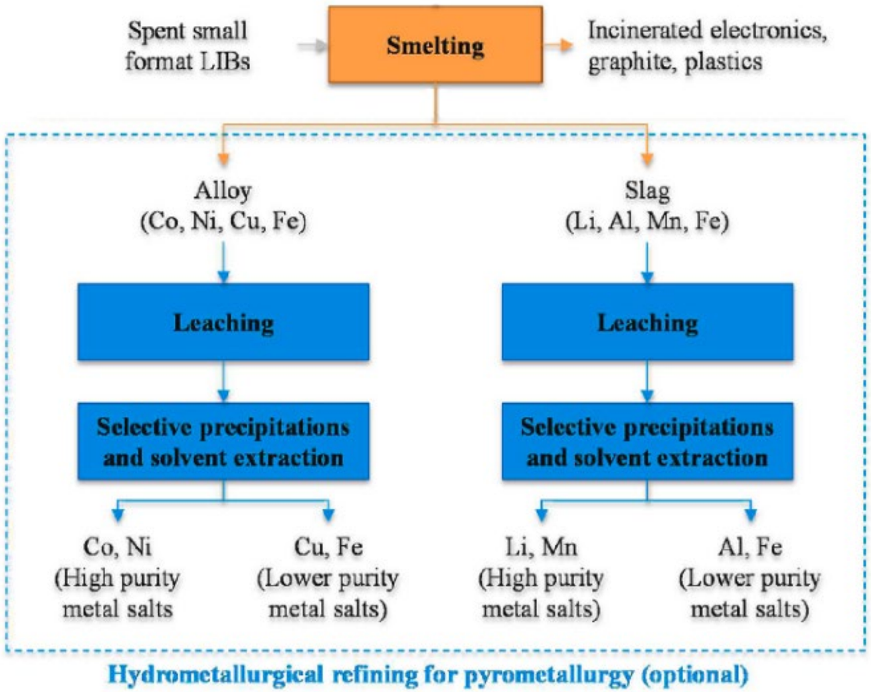


Figure C17: Umicore LiPo battery smelting process

Enclosure

Plastic sourcing
Although the electronics are the main contributor to the footprint of the current TRACK this does not rule out the need to critically look at opportunities to decrease the footprint of the TRACK enclosure as well. Both parts of the housing are injection moulded with an ABS-PC blend.
Currently the product is made from virgin plastics that are derived from a relative energy intensive refinement process of fossil fuels in oil refineries. Furthermore additives are sourced that need to prevent degradation by sunlight or add colour to the product.

Use phase
The inherent durability of (engineering) plastics means that incorrectly disposed items will remain in the environment for generation which will result in leaching of toxic additives and the contamination of ecosystems and the food chain with microplastics.
Finally there is the problem that additives are leaching into the environment due to chemical, salts or other exposure in the use context.

Plastic recycling
Plastic recycling will be discussed in detail in chapter 5.5

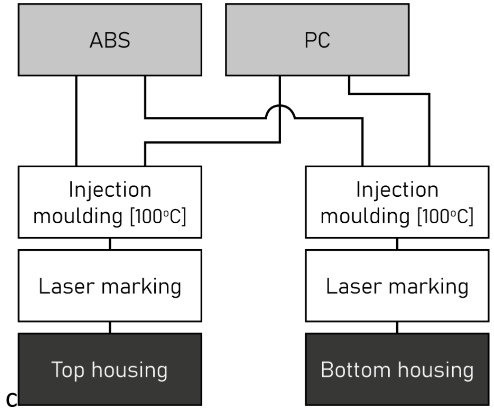


Figure C18: Plastic housing parts production

C8: Other TRACK components

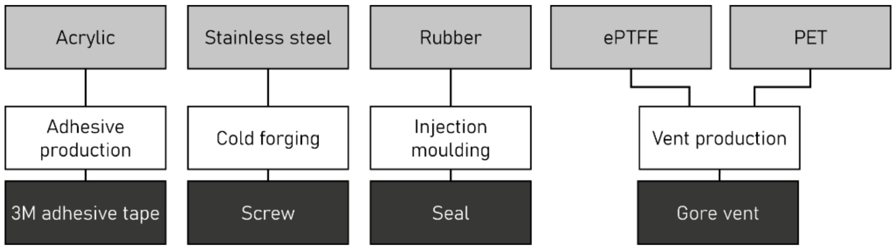


Figure C19: Overview other components production (out of scope of LCA)

Appendix D1: Disassembly

Sources: (NEN, 2019), (TU Delft, 2020), (TU Delft, 2022), (Philips, 2021)

CRITERIUM	PARAMETER	WEIGHT	BATTERY	PCBA	PV PANEL	
Documentation	Add an identifier on the product to make disassembly documentation of the product traceable	1	■	■	■	
Locating access points and fasteners	Indication of where access points are located (e.g. by markings or making clear where and how to connect the diagnostic equipment to the product)	1		■		
	Indication of where fasteners are located	1		■		
	Provision of diagrams/drawings with the location of access points and fasteners.	1				
Accessibility of parts	Ability to handle parts (e.g. they are not too small, bulky, heavy, soft, sticky or sharp, they do not have a tendency to tangle)	3	■	■	■	
	Access to parts during disassembly	3	■	■		
	Modularity of the parts	1				
	Access to fasteners, e.g. joints, gripping points and breaking points	3		■		
	Asymmetry/symmetry of parts (e.g. to ensure correct assembly)	2		■	■	
	Ability of parts to be secured directly upon insertion without any extra operations after the insertion (e.g. screwing, tightening or gluing)	1	■			
Fasteners and connectors	Reusable	4		■		
	Removable without risk of causing damage or leaving residue	3		■		
Tools	No tool	A [**4**]				
	Tool or set of tools that is supplied with the product or spare part	B [**3**]				
	Basic tools as listed in appendix	C [**2**]	■	■		
	Other commercially available tools	D [**1**]	▒	▒		
	Total points	**28**	**8**	**21**	**4**	
	Disassembly score		**29 %**	**75 %**	**14 %**	**39 %**

Appendix D2: Maintenance

Sources: (NEN, 2019), (NEN, 2020), (TU Delft, 2020), (TU Delft, 2022), (Philips, 2021), (C2CPII, 2021)

CRITERIUM	PARAMETER	WEIGHT	BATTERY	
Disassembly	Ease of disassembly and assembly	**10**	29 %	
Product cleaning	Avoid nooks, small holes, grooves etc which can capture dirt and dust.	**1**		
	Materials and markings being able to withstand cleaning agents (either chemical or mechanical)	**1**		
Product diagnostics	Diagnosis by a signal that can be understood without the need for any supporting documentation or software	A [**4**]		
	Diagnosis with supporting documentation, through consulting a fault-finding tree or through reading and/or entering codes, supplied with the product and/or are publicly available	B [**3**]		
	Diagnosis through the use of hardware and/or software which is publicly available	C [**2**]		
	Diagnosis using proprietary tools for the diagnosis, change of settings or transfer of software, which are not included with the product	D [**1**]		
Spare parts	Available for a duration of time that reflects the expected durability	A [**3**]		
	Available for a duration of time that reflects the expected average durability	B [**2**]		
	Available during a period of two years after the time of sale	C [**1**]		
	Total points	**19**	**5**	
	Maintenance score		**26 %**	**26 %**

Appendix D3: Refurbishment/Repair/Remanufacturing

Sources: (NEN, 2019), (TU Delft, 2020), (TU Delft, 2022), (Philips, 2021), (C2CPII, 2021)

CRITERIUM	PARAMETER	WEIGHT	BATTERY	PCBA	PV PANEL	
Disassembly	Ease of disassembly and assembly	**10**	29 %	75 %	14 %	
Return options	Comprehensive return (Pickup service for defective products or a replacement product)	A [**3**]				
	Basic return	B [**2**]				
Data transfer and deletion	Factory reset	A [**2**]				
	On request	B [**1**]				
Diagnostic support and interfaces	Diagnosis by a signal that can be understood without the need for any supporting documentation or software	A [**4**]				
	Diagnosis with supporting documentation, through consulting a fault-finding tree or through reading and/or entering codes, supplied with the product and/or are publicly available	B [**3**]				
	Diagnosis through the use of hardware and/or software which is publicly available	C [**2**]				
	Diagnosis using proprietary tools for the diagnosis, change of settings or transfer of software, which are not included with the product	D [**1**]				
Spare parts	Available for a duration of time that reflects the expected durability	A [**3**]				
	Available for a duration of time that reflects the expected average durability	B [**2**]				
	Available during a period of two years after the time of sale	C [**1**]				
Product cleaning	Avoid nooks, small holes, grooves etc. which can capture dirt and dust.	**1**				
	Materials and markings being able to withstand cleaning agents (either chemical or mechanical)	**1**				
Process cycles	Materials and fasteners are sufficiently strong to be reprocessed one or more times	**1**				
	Total points	**25**	**9**	**13**	**4**	
	Refurbishment score		**35 %**			**35 %**
	Repair score		**35 %**	**50 %**		**43 %**
	Remanufacturing score		**35 %**	**50%**	**18 %**	**23 %**

Appendix D4: Reuse

Sources: (NEN, 2019), (NEN, 2020)

CRITERIUM	PARAMETER	WEIGHT	SCREWS	BOLTS	RIVETS	ZIP-TIES	
Documentation	Add an identifier on the product to make documentation of the product traceable	**1**	■	■	■	■	
Fasteners and connectors	Reusable	**3**	■	■			
	Removable without risk of causing damage or leaving residue	**2**		■		■	
Type of tools	No tool/Hands	A [**4**]					
	Tool or set of tools that is supplied with the product or spare part	B [**3**]					
	Basic tools as listed in figure X	C [**2**]	■	■		■	
	Other commercially available tools	D [**1**]	▒	▒	■	▒	
Data transfer and deletion	Factory reset	A [**2**]	■	■	■	■	
	On request	B [**1**]	▒	▒	▒	▒	
Product cleaning	Avoid nooks, small holes, grooves etc. which can capture dirt and dust.	**1**	■	■	■	■	
	Materials and markings being able to withstand cleaning agents (either chemical or mechanical)	**1**	■	■	■	■	
Determine condition	Information on how to determine its functionality	**1**					
	Information on the status of the functionality (e.g. if the different functions are still operational)	**1**					
	Total points	**14**	**10**	**12**	**6**	**9**	
	Reuse score		**100 %**	**100 %**	**43 %**	**64 %**	**66 %**

Appendix D5: Recycle

Sources: (NEN, 2019), (PolyCE, 2021), (Ecosystem, 2022), (TU Delft, 2020), (TU Delft, 2022), (C2CPII, 2021), (Philips, 2021)

See next page >>>

Connections		Recyclability	
Class	Members	Manual dismantling	Mechanical disintegration
Clicking	Annular click fingers	Good	Good
	Straight click fingers	Good	Good
	Tilting click fingers (separate part)	Good	Good
	Clicking	Good	Good
Pressing	Large contact area, low contact stresses (e.g. large cylindrical parts)	Good	Good
	Small contact area, high contact stresses (e.g. cross shaped pins)	Good	Good
Mechanical fastening	Screwing (both parts have injection molded thread features)	Good	Good
	Springs	Good	Good
	Screw	Good	Average
	Bolt	Good	Average
	Nut	Good	Average
	Speed nuts	Good	Average
	Snap fit	Good	Average
	Push pins	Good	Average
	Rivet	Bad	Average
Cold forming technique/ Intergral fasteners	Hemming	Good	Good
	Folding	Good	Good
	Crimping	Good	Average
	Clinching	Average	Average
Staking	Heat staking	Average	Good
	HACS (hot air cold staking)	Average	Good
Adhesive bonding	Pressure sensitive adhesives	Good	Average
	Silicones (SIL)	Average	Average
	Hot-melt Adhesives	Average	Average
	Polymer based glue	Bad	Bad
	Silicone based glues	Bad	Bad
	Cements	Bad	Bad
	Acrylic Adhesives	Bad	Bad
	Cyanoacrylate Adhesives	Bad	Bad
	Epoxies and Epoxy-Phenolics	Bad	Bad
	Imide-based Adhesives (Dismaleimides, BMI and Polyimides, PI)	Bad	Bad
	Phenolic Adhesives	Bad	Bad
	Polyurethanes	Bad	Bad
	Ceramic-based Cements	Bad	Bad
Soldering	Soldering	Average	Bad
Brazing	Brazing	Bad	Bad
Welding	Induction welding (with metal wire or insert)	Good	Average
	Heat sealing (common in packaging)	Average	Average
	Ultrasonic welding	Bad	Good
	Friction welding	Bad	Bad
	Spin welding	Bad	Bad
	Mirror welding	Bad	Bad
	Laser welding	Bad	Bad
Molded connection	Insert molding	Bad	Bad
	Outsert molding	Bad	Bad
	In mold labeling	Bad	Bad
	2K molding	Bad	Bad

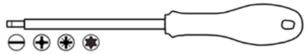
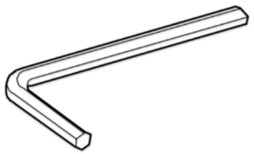
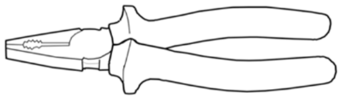
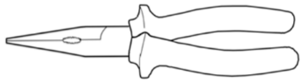
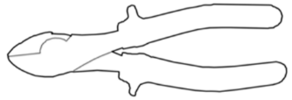
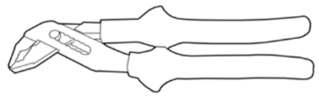
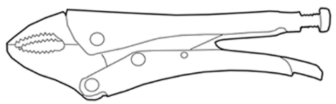
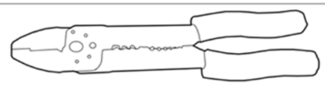
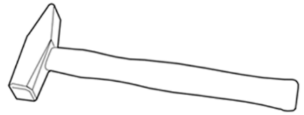
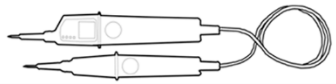
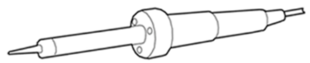
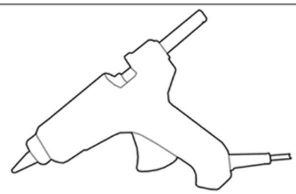
Good Average Bad

Figure D1: Recyclability of connection type (Bakker, 2019)

CRITERIUM	PARAMETER	WEIGHT	SOLAR	
Material general	Minimize the variety of materials	2	■	
	Avoid composites	1	■	
	Use markings to identify the type of material used in components, for plastics use ASTM International Resin Identification Coding System			
	Avoid substances that are listerd for future restriction in the SIN list https://sinlist.chemsec.org/	3	■	
	Avoid Substances of Very High Concern (SVHC) according to REACH and substances classified carcinogenic (Carc. 1A or 1B), mutagenic (Muta 1A or 1), reprotoxic (Repr. 1A or 1B) by CLP Regulation	3	■	
	Avoid foam	1	■	
Product Passport	Add an identifier on the product to make documentation of the product traceable	3		
Housing Connections	Avoid connections that have a bad recyclability score in the overview of disintegration and dismantling of connections of figure X	1	■	
	Avoid connections that enclose a material permanently such as moulding inserts, rivets, staples, press-fit, bolts, bolt and nut, brazing, welding and clinching	2	■	
	Minimize the use of magnets	1	■	
	Avoid the irreversible connection of ferrous and non-ferrous metals (e.g. copper and steel)	2	■	
Plastics	Avoid thermosets	2	■	
	Avoid polymer blends (except PC/ABS)	3	■	
	Avoid halogenated polymers (e.g. PVC, PTFE)	3	■	
	Minimize the use of thermoplastic elastomers	1	■	
	Avoid thermoset-rubbers	2		
	Avoid 2K moulding of different types of plastic	3	■	
	Avoid coatings such as painting, lacquering, plating, galvanizing and vacuum-metallization	2	■	
	Avoid stickers	1	■	
Plastic fillers	Avoid fillers (mineral e.g. glass fibre or organic)	2	■	
	Avoid Brominated Flame Retardants (PBDEs, TBBPA, PBBs, HBCDs, etc.)	3		
	Minimize other additives in plastics	1		
PCBA	Use a module for hazardous components in the product structure	1		
	Get PCBA out in one piece during dismantling	2	■	
	Use clips, click fingers, press fit, shrink foil or connectors but no permanent fixing (tapes, glue, melting and welding).	2	■	
	Avoid magnetic components on PCBs	1	■	
Battery	Preferably place cells and batteries so they are readily accessible without dismantling the product, using for example, a hatch, a snap-fit cover.	3		
	Use click/snap solutions to fix batteries in a product. Avoid permanent fixing such as glued, welded and enclosed solutions.	2		
	Avoid welding the battery directly on the PCB.	2	■	
Solar Panel	Avoid encapsulants (e.g. EVA)	2		
	Avoid fluorinated backsheet (e.g. Tedlar/PVF)	2		
	Lead-free Solar Panel	2	■	
	Total points	**55**	**42**	
	Recycling score		**69 %**	**69 %**

Appendix D6: List basic tools

Source: (NEN, 2020)

Tool type	Illustration (informative example)	Reference
Screwdriver for slotted heads, cross recess or for hexalobular recess heads		ISO 2380, ISO 8764, ISO 10664
Hexagon socket key		ISO 2936
Combination wrench		ISO 7738
Combination pliers		ISO 5746
Half round nose pliers		ISO 5745
Diagonal cutters		ISO 5749
Multigrip pliers (multiple slip joint pliers)		ISO 8976
Locking pliers		
Combination pliers for wire stripping and terminal crimping		
Prying lever		
Tweezers		
Hammer, steel head		ISO 15601
Utility knife (cutter) with snap-off blades		
Multimeter		
Voltage tester		
Soldering iron		
Hot glue gun		
Magnifying glass		

NOTE 1 Most tools come in different sizes. This list only refers to the tool type. Although some sizes are more common than others, for practical purposes, any size of the listed tools is considered to be a basic tool.

Appendix E: Network & communication technologies

Frequency selective surfaces (passive)

Frequency selective surfaces (FSS) can be used to either filter, bloc or reflect radiofrequency (RF) signals emitted at a specific frequency, while remaining transparent to RF signals at other frequencies. An FSS is completely passive and designed with a specific line pattern that is screen printed on a flexible substrate using conductive inks (figure E2).
The application of the surfaces is currently aimed at eliminating signal dead-zones or enhance 5G coverage in dense urban areas or stadiums (e2ip, 2021). In case of the TRACK it might also provide an opportunity for boosting its signal by using the surface of the asset as a concentrator of the signal beam (figure E1d).

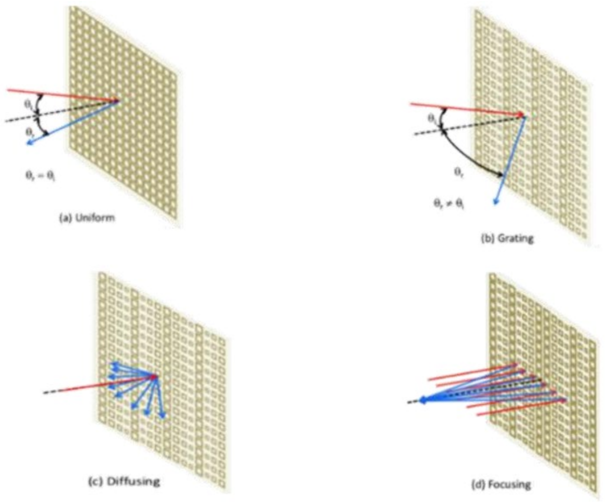


Figure E1: Different printed patterns and their effects on incoming signals

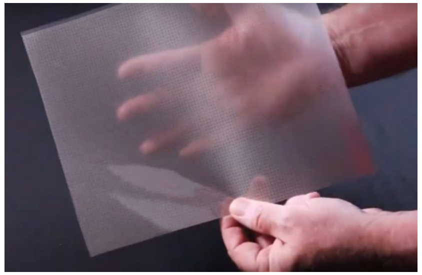


Figure E2: Sample of FSS showing its flexibility and transparency

Reconfigurable intelligent surfaces (active)

A challenge for mmWave (5G Advanced/6G) is that frequency is very susceptible to blockage by objects such as walls or even the human body (figure E3).
Reconfigurable Intelligent Surfaces (RIS) aim to boost signal performance indoors and in dense urban areas by acting like an intelligent mirror for radio signals. The mirror (RIS) is made of a new type of passive metamaterial, which consists of a large number of reflecting elements that can be individually controlled. In the future it could also harvest the energy contained in the reflected radio signals directly for to power its reconfiguration.

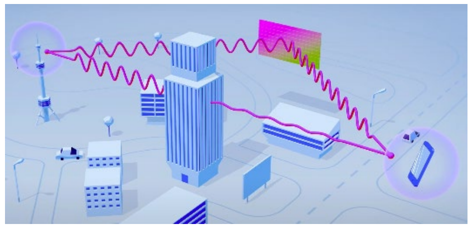


Figure E3: RIS employed in an urban area to boost the signal

Appendix F1: PCB historical perspective

From art and photography to printing circuits

To understand the confusion about the terminology and to understand why PE seems to be gaining some traction at the moment, it is useful to look at the development of PCB design.

Subtractive PCB production method

Fundamentals of subtractive PCB production method

The origins of PCB manufacturing can be traced back to a method for producing ornamental panels using an acid bath (Petherbridge, 2005). Baynes (1888) used an acid resist pattern layer to cover the parts that need to be protected from being etched away to produce the panel (figure F1). According to his patent (United States Patentnr. US378423A, 1888) the acid resist could be applied in two ways:

1. Printing the pattern directly by the use of a lithographic press.
2. Cover the panel completely with a resist sensitive to light and creating the pattern using a negative image similar to the developing process in [analogue] photography.

While the first method is indeed based on a printing technique, the second method is based fundamentally on a technique from photography.

Competing with "bird's nests"

It is the first print-based technique that made it from the laboratory to a mass produced commercial product: a radio for a music printing company in 1942 (figure F2a). The PCB in this product was designed by Paul Eisler (United States Patentnr. US2441960A, 1948). Eisler is often referred to as 'the intellectual father of the PCB' and had a background in the newspaper and magazine printing industry. He used etched copper foil, which had just been invented in 1937 (Gasch, 2016), and laminated it to varnished paper (Serban, 2014). Although this radio showed the potential of the technology for mass production, other radio manufacturers were hesitant to adopt it (how2electronics, 2022).

Until then circuits were made using manual point-to-point soldering technique, which could result in socalled "bird's nests" (figure F2b). However the initial investment cost for PCB production was higher than manual wiring. "Our girls are cheaper and more flexible" one manufacturer apparently told him (Kluger, 2023), but also the shortage of copper during WWII (Gasch, 2016) may have played a part in the initial lack of success.

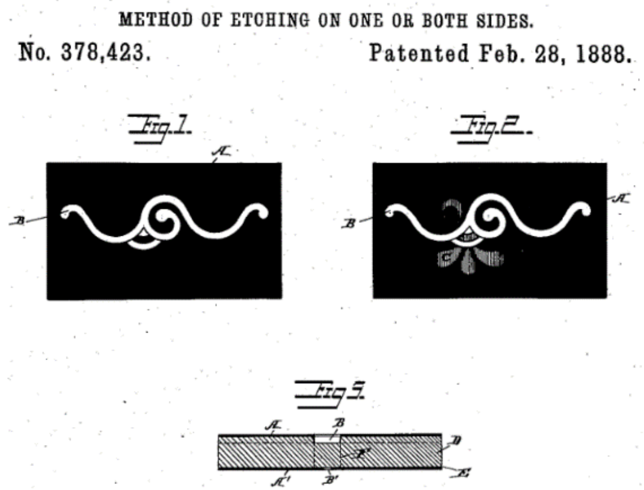


Figure F1: Method of etching to create decorative art

Adoption by the US army

However, during the war the US army found out about Eisler's wiring method and became interested because it had the potential to both improve the reliability of the detonation element in their munition, while at the same time increase production volumes.

Introduction to the masses

Some time after WWII, the US army made the patents of their further refined PCB production process public. Combined with the introduction of mass soldering by solder wave (Kluger, 2023) in the 1950s, the subtractive PCB production method introduced by Eisler, soon became the main driver for the rise in low-cost mass production of electronics. It took till at least the late 1960s before the point-to-point soldering was fully superseded by components attached to a PCB.

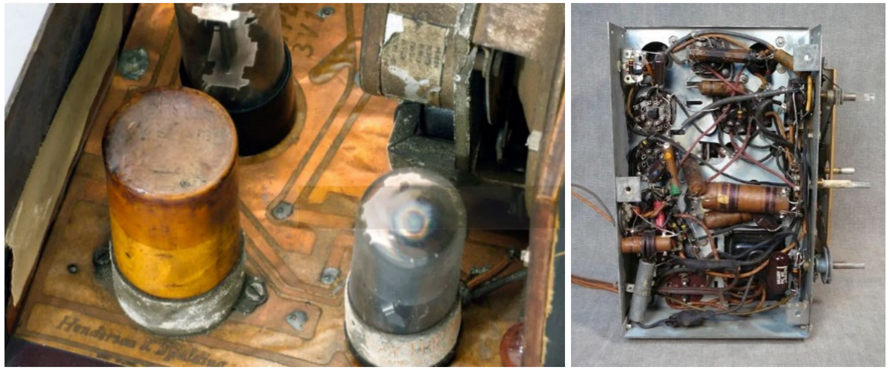


Figure F2: (a) Paul Eisler 1942 radio with PCB, (b) GE radio from1937 with point-to-point wiring

Shift to photography based etching

A major shift in PCB manufacturing method came through innovations in photopolymer imaging in the early 1960s. This led to the invention of dry film photoresists for electronics by DuPont (DuPont, 2021). Until then photosensitive materials were not effective enough to completely protect the covered surface during the etching step (figure F3), leading to unreliable connections (Petherbridge, 2005). The improved accuracy of the new dry film photoresist made that Baynes' original second (photography-based) patterning method could now be introduced in mass-production as well. Dry etching is the default manufacturing process for PCBs up to this day.

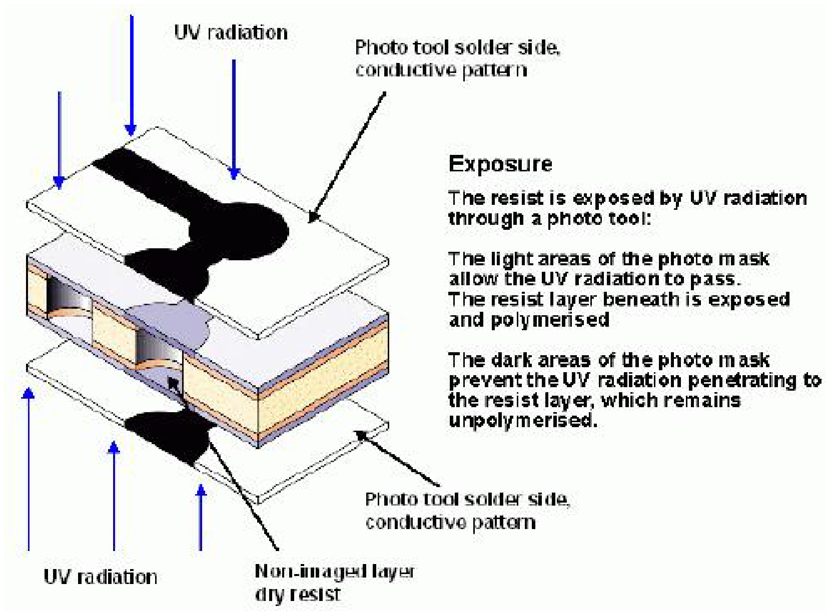


Figure F3: PCB imaging step

Through-hole mounting to surface-mounting

Over time miniaturization (increasingly higher component density requirements, higher pin densities for integrated circuit components, more space for inner layer traces) and component placement on both sides of the board were proving difficult for traditional through-hole PCB assembly. In the 1960s Surface Mount Technology was introduced by IBM (Wikipedia, 2022) to meet the new requirements.

Unfortunately increasing component densities makes on-board component-level repairs or upgrading of components (using for example component sockets) much more difficult (imagine reworking the PCB of figure F4 ☹).

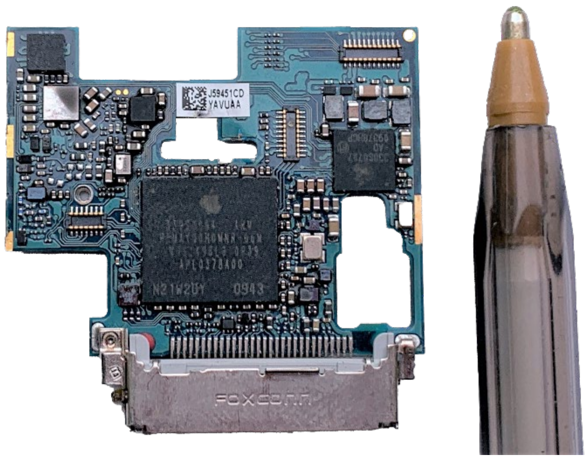


*Figure F4: High Density Interconnect (HDI) PCB of iPod Nano 4th gen (2008) (with BIC pen for scale***)**

Digital photoresist

And although the etching process in essence still resembles the one envisioned by Baynes in 1888, there is one notable advancement next to the use of dry film photoresist. Until recently the photoresist was cured using UV light that was projected via a negative image of the circuit design on the photoresist. The negative image that was required in the photo tool (figure F3) needed to be physically printed. Nowadays the physical photo tool image is no longer needed as it is replaced by a digital technique: high-resolution Direct Laser Imaging (Sierra Circuits, 2021).

Subtractive IC production

It is also worth noting that this subtractive method (of using photoresist) is the basis of photolithography, which is the fundamental production method for integrated circuit wafers (ASML, 2023). In this case the physical image or ‘photomask’ as it is called (figure F5) is still used to project the EUV light on to prepare the etching of every layer of the chip.

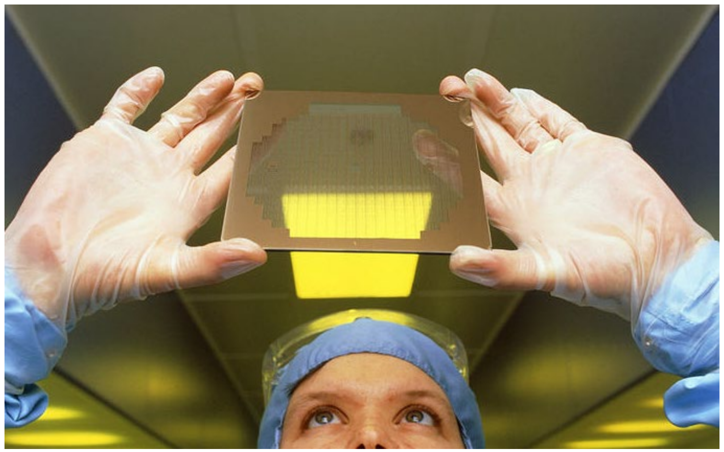


Figure F5: Photomask for IC lithography

Additive PCB production methods

Battle for commercialization

Before the subtractive method of etching became the dominant PCB manufacturing technology, several alternative production methods were patented. Remarkably some of those patents already describe additive production methods.

For example, Hanson (1903) stated in his patent that he had created conductors "*in situ* by electrodeposition or by mechanical deposition as for example, ruling lines of metallic powder in a suitable medium directly upon the layer of insulating material" (Petherbridge, 2005). His patent shows the concept of conductive inks, which is still the main additive PCB production method used today.

Building on this idea was the first (but unsuccessful) attempt of the commercialization of printed circuit board by Parolini (1927) (figure F6). The traces were produced using inks with metal powder and afterwards electroplated to achieve the required thickness for conduction. U-shaped metal plates acted as bridges over the traces. It is unknown why this attempt proved unsuccessful.

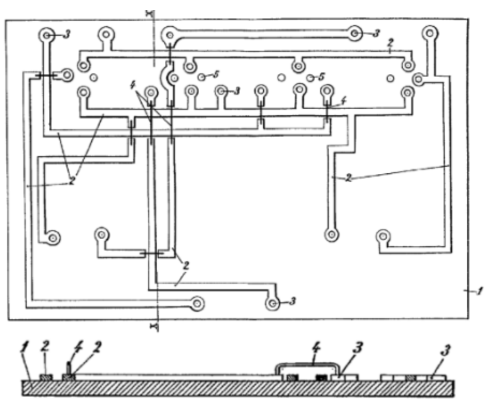


Figure F6: Additive circuit layout by Parolini 1927

Rediscovery of additive PCB production

Likely because of the success of the subtractive method, the interest in additive technologies was virtually absent until 1995. This means that the technological developments were also halted and many concepts familiar to subtractive PCB design (e.g. integration of SMT technology (from 1960s-1980s) or multilayer circuit designs (from 1990s)) had to be reinvented as an additive method later on.

In a 'rediscovery' paper (Harrison, 1995) of the additive method three things are noticeable:

1. The title: *Novel circuit fabrication techniques for reduced environmental impact.* In this paper additive PCB design is already framed as a more sustainable alternative.
   However reducing environmental impact in this case has to be seen in the light of increasingly stricter pollution limits by water authorities to restrict copper in the waste water and the use of hydrocarbons [fossil fuels] in photoresist developer and stripper solutions.
2. The acknowledgement that only faster printing speed will help the additive method to outperform the mature subtractive method on cost. The study proposes to use the high speed offset lithographic printing technique, the standard for the graphical printing industry at the time.
3. The novel design opportunities for using less material and better recycling: "use the casing material of the product as a substrate material to move towards a monomaterial approach which eases recycling problems."

Appendix F2: FHE production methods

Printing methods

Production methods for printed electronics are once again taking over analogue printing techniques from the graphical industry of printing magazines, newspapers on paper or graphics on fabrics. Those converted technologies, include **flexography, gravure, offset printing** and **screen printing**. To get the economies of scale the printing electronics is usually performed roll-to-roll, but sheet-to-sheet options are also available. Next to traditional printing techniques from the printing industry there is also the digital **inkjet printing** technique.

Figure F7: Roll-to-roll screen printing production line

Choosing a suitable printing method depends on production volume (throughput) and accuracy requirements (see figure F8). The most common method is roll-to-roll screen printing (figure F7), but there are also some more exotic production methods that are specifically invented by the Dutch TNO/Holst Centre for printing of electronics. For example technologies such as impulse printing and Laser Induced Forward Transfer are currently being commercialized by spin-off companies.

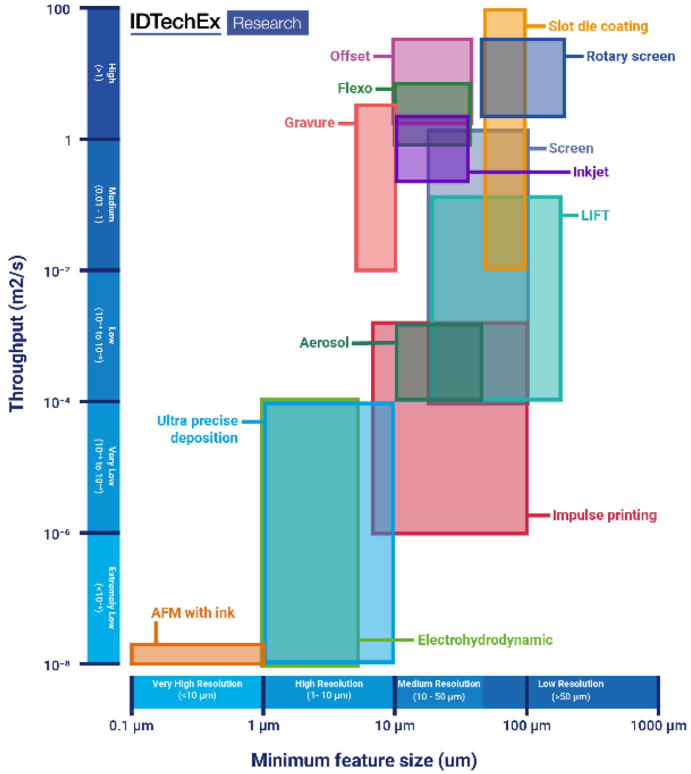


Figure F8: Printing methods for electronics mapped on speed and accuracy

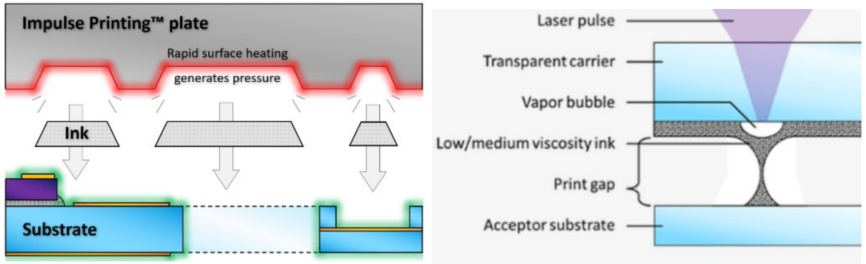


Figure F9: (a) Impulse printing method, (b) LIFT printing method

Impulse printing
This analogue printing technique is called impulse printing because the metallic ink is fired onto the substrate by at 1 million G (figure F9a). Due to rapid heating of the solvent on the stencil plate, the solvent will start to boil, building up enough pressure to fire the ink. (FononTech, 2023)

Laser Induced Forward Transfer (LIFT)
This technique has similarities with impulse printing as it also uses expanding gas heated by a laser to fire ink from the carrier substrate onto the target (acceptor) substrate (Keiron, 2023) (figure F9b). The main difference is that LIFT is a digital technique where a laser is fired tens to hundreds of thousands of times per second to heat the ink.

Inks

Conductive
The most popular metal inks are silver, copper, gold and aluminium. Silver-based inks dominate the market as they both have high conductivity and are very stable over time (Dimitriou, 2021), but the high price hinders their use for mass production. Copper-based inks on the other hand have a much lower price (Copprint, 2023) and only slightly less (6%) conductivity (see figure F10), but are held back by stability concerns as potential oxidation lowers the conductivity over time. There are several methods to prevent oxidation, such as the use of antioxidants, organic solvents, the formation of a dense shell of non-oxidizable conductive material or a biometallic core-shell (Wiklund, 2021).
Another option is the use of highly, stable and low-cost conductive polymers such as graphite or carbon nanotubes (Williams, 2021). However conductive polymers usually have lower electrical conductivity than metallic materials, their production is challenging and they have long drying times.

Dielectric
Dielectric inks are used as an insulator layer and allow for circuitry crossovers, multilayer circuits and act as a shielding layer, conformal coating or an encapsulation layer.
Commonly used dielectric inks consists of acrylates, various thermoplastic polymers or polyester resins (Henkel, 2023).
Finally, although highly experimental, it might be possible to print an all-carbon recyclable circuit in the future by combining conductive polymer inks with a crystalline nanocellulose dielectric ink (Williams, 2021).

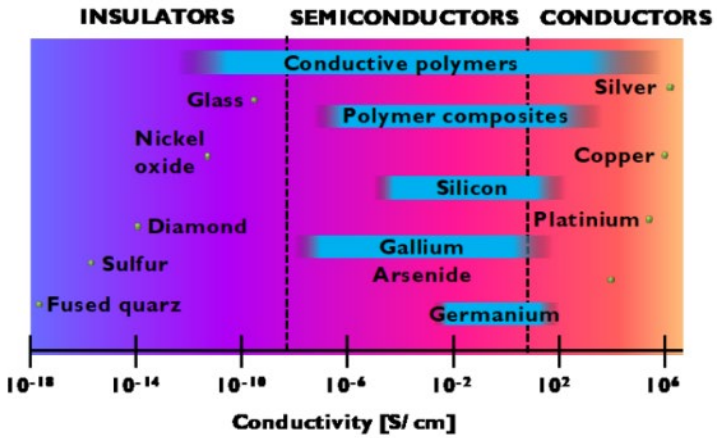


Figure F10: Conductivity of inking materials

Post-printing methods
To remove the additives and solvents from the inks and allow for a continuous, highly conductive layer to be formed, a post-print treatment step is necessary. The preferred treatment method, such as photonic curing, annealing, thermal-, photonic-, microwave-, plasma- or chemical sintering, depends on the specific substrate and ink requirements (Dimitriou, 2021).

Substrate
The substrate is the base for the rest of the electronics and acts as an electric insulator to separate electric devices from each other. Currently it is not possible to recycle the FR-4 composite material and in the best case it is used as feedstock in the smelting oven used for extracting valuable metals from the PCBA. In the case of PE various lower impact or circular materials are used as substrate (see figure F11)

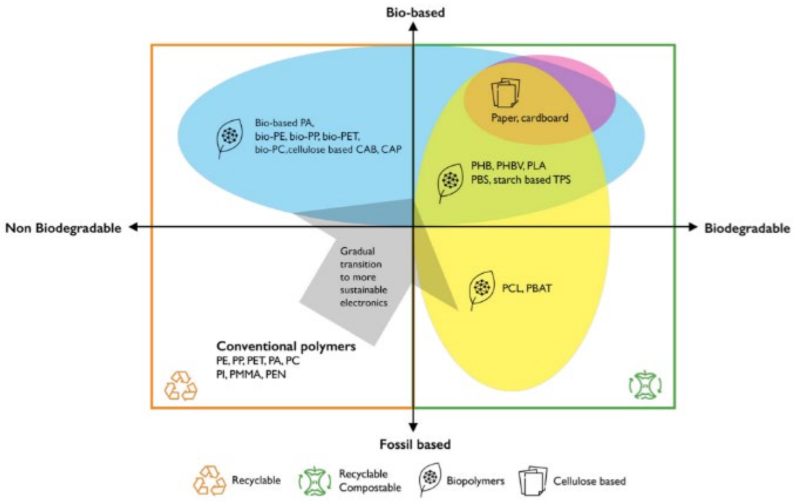


Figure F11: Categorization of alternative PE substate materials

Substrate Material	Glass Transition Temperature (°C)	Maximum Service Temperature (°C)	Comments
PET	68–80	115–120	Recyclable, excellent water resistance
PEN	118–126	160–180	Recyclable, excellent water resistance, good UV durability, transparent
PI thermoplastic	240–260	221–241	Recyclable, expensive, excellent water resistance, excellent UV durability
PC	142–158	101–116	Recyclable, excellent water resistance, transparent
PLA	52–60	45–55	Recyclable, biodegradable, good UV durability, transparent, highly renewable material content
PCL	(−72)–(−59)	40–50	Recyclable, biodegradable
PLGA	44–54	45–55	Recyclable, biodegradable, expensive, good UV durability, transparent
PU thermoplastic	77–107	65–78	Recyclable, biodegradable, excellent water resistance, transparent
Paper	47–67	77–130	Recyclable, biodegradable, highly renewable material content
Starch	10–20	60–80	Recyclable, biodegradable, highly renewable material content

Figure F12: Glass transition temperatures, maximum service temperatures and other notable properties of common substrate materials

Virgin plastics
The most commonly applied substrate materials (see figure F12) are virgin plastics such as PET, PEN, PI and PC; with PET being the industry standard because of its flexibility, solvent resistance and low cost (Wiklund, 2021).

Recycled plastics
While it is still very rarely done, it is possible to replace the virgin material with a high quality recycled variant. For example a rPET substrate can be used for a design based on PET (Välimäki, 2020).

Biobased materials
However, more common are biobased substrates. Several companies are already offering them and the most well-known is the British company Jiva Materials. It uses a jute fibre reinforced polymer in its product: Soluboard. Soluboard is for example proposed in Dell's Concept Luna (Dell, 2021) and investigated by Microsoft for application in products such as a computer mouse shown in figure F13 (Jiva Materials, 2022).

Furthermore biobased plastic variants can be applied. When studying the performance and durability against heat, humidity and solvents biobased PET and PLA were found to achieve best results (VTT, 2022).

Biodegradable materials

A final category are biodegradable substrates such as paper. Paper substrate is an attractive alternative for printed electronics, since it is cheap, flexible, environmentally friendly and biodegradable. The disadvantages of paper such as poor moisture resistance can be improved by applying a (biodegradable) coating or by lamination.

Another suitable natural polymer substrate is nanocellulose, which possesses properties such as high transparency, mechanical strength, heat resistance, low thermal expansion.

And furthermore there are some more experimental materials such as bacterial cellulose (Geigera, 2021) and mycelium (Danninger, 2022).

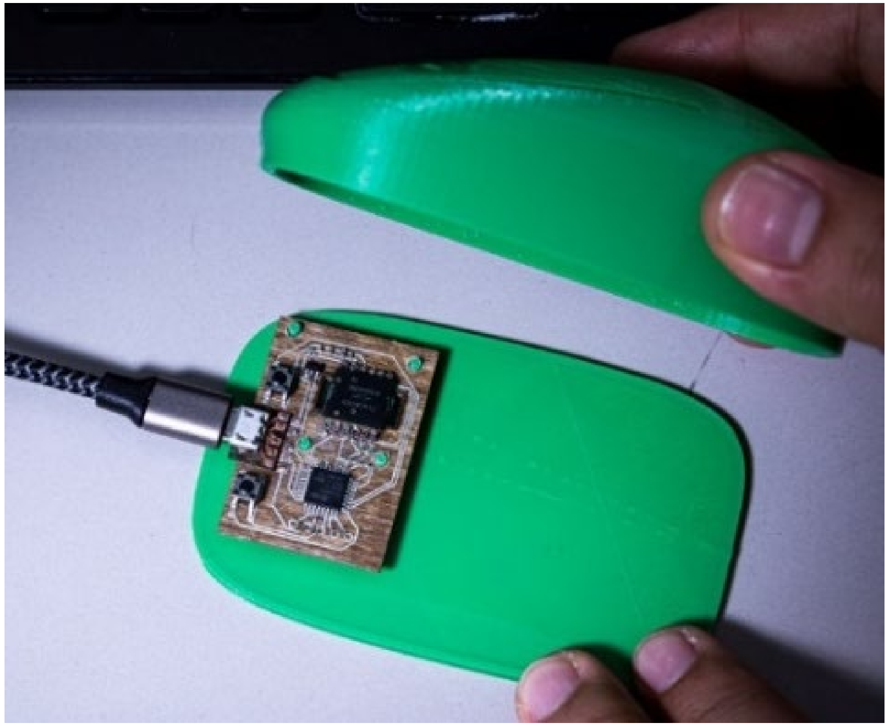


Figure F13: Microsoft research PC mouse prototype with Soluboard biobased PC

Appendix F3: FHE and circular electronics development

FHE development barriers

Limited conductivity

Printed conductors have typically over ten times higher resistance than the copper wires on the PCB. This forces to careful layout planning together with schematic design. Another option could be to still use etched copper for the wires that require higher conductivity while printing the rest. However current design tools do not support this hybrid form of PCB design (PrintoCent, 2019).

Design software and kits

The various different design tools and their documentation are still in their infancy as they are mainly based on different research projects. They do not support electronic design automation (EDA) and thus require more manual labour from the designer. Furthermore standardization and interoperability between development tools of different companies has not been considered yet (PrintoCent, 2019).
However the industry standard PCB design software tool Altium has introduced a Printed Electronics feature in their Altium Designer 19 (Altium, 2019). This could lower the barrier and introduce some form of standardization, however it is unclear to what extend it is interoperable with the tools within the industry and to what extend SODAQ hardware design team could use them for design.

Circular Electronics research projects

During the research two research projects were discovered that, according to their description are in line with the goals for the next generation TRACK PCBA.

ECOTRON

“The goal of the ECOTRON project is to improve the recyclability of printed electronic devices through a multidisciplinary approach including the introduction of biobased materials, innovative printing processes and device and module disassembly technologies. In addition, industrially scalable recycling standards and technologies will be developed.”
(Holst centre, 2022)

Circular Circuits

“The circular circuits project will develop a fully circular generation of electronics. It will develop solutions to overcome technical, economic and societal bottlenecks for lifetime extension, reuse, repair, refurbishment and recycling through development of a new generation of electronic components, product-service design, new business models and advanced recycling technology” (M2i, 2023).

Unfortunately both research projects were approached unsuccessfully.

Appendix F4: Interview InnovationLab

Research institute InnovationLab was contacted for a discussion about possible opportunities for a FHE design. The following point can be concluded about their sustainable and cost-efficient solution for replacing traditional PCBs (InnovationLab, 2022):

- The printing process meets the minimum dimensions for the SMT components such as trace width, pitch and contact pad size.
- InnovationLab can print two layer circuits using its screen printing roll-to-roll manufacturing line (see figure F14), while the current TRACK PCB features a 4-layer design. Adding more layers would be possible in the future, but a timeframe was not provided.
- The initial investment costs are much higher than traditionally. Both due to the investment in converting the current design into an AM design ready for use by InnovationLab. Secondly, the screen printing line would have to be converted in case two layer design would not be feasible and finally there is the investment in the screen printing rolls.
- Price estimation would start for around 100,000 circuits, while only 10,000 TRACKs are made per year.
- Copper ink is used instead of silver to bring down cost. However, if the ground plane layer for the antenna design would need a full layer of copper ink to be printed, this would be extremely costly and alternatives would need to be explored.
- Prototyping can be performed manually using transferring ink to the surface using a screen mask and a squeegee rubber.
- InnovationLab prefers traditional SMT reflow technology over alternatives as they experienced that photonic soldering could damage ink close to the heated solder pad, while anisotropic adhesive did not always provide a reliable connection.

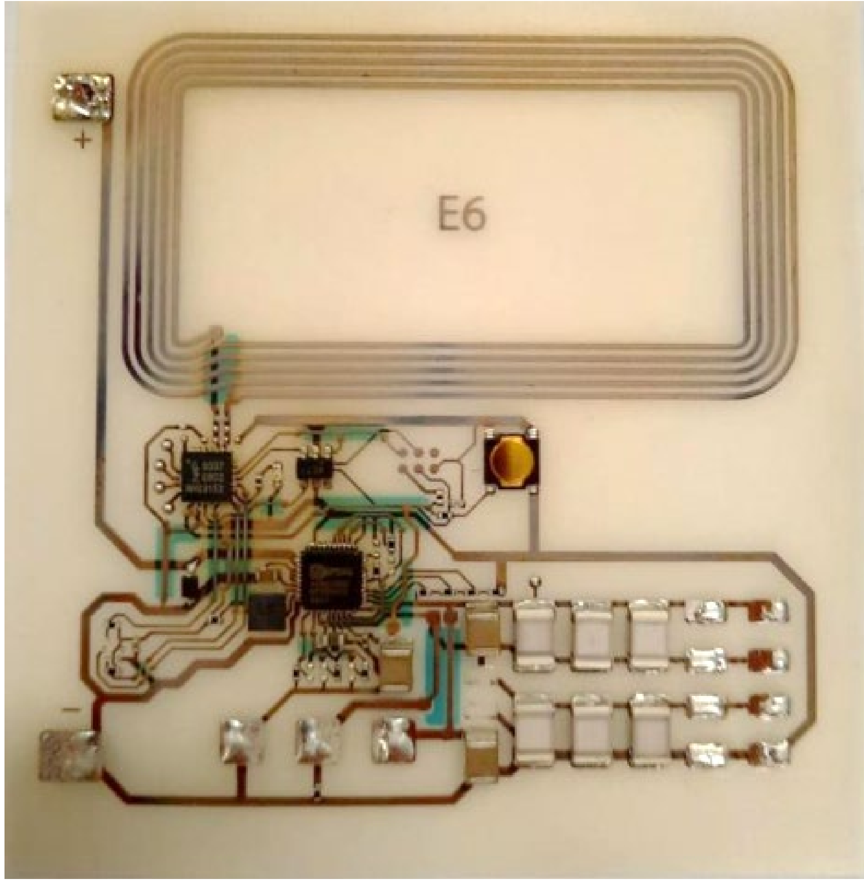


Figure F14: InnovationLab RFID Smart Tag 2 layer example circuit

Appendix F5: Interview TracXon questions

Technical requirements

- Can TracXon's printing processes meet the minimum dimensions for the TRACK (e.g. for the SMT components)

PARAMETER	MINIMUM DIMENSIONS [mm]
Trace width	0.15
Pitch	0.5
Contact pad size	0.3 x 0.3

- How many layers can TracXon achieve (TRACK has currently a four layer design)?
- Is it possible to print double sided and what options are there to replace vias?
- Can TracXon also apply copper ink instead of silver to bring down cost?
- What would be the conductivity loss compared to an etched copper traces?
- What would be a cost-effective way to replace the current ground layer made out of an entire layer of copper?
- What are the opportunities and challenges of replacing passive SMDs with printed ones?
- What is TracXon's experience with low power soldering alternatives such as photonic sintering/soldering or anisotropic adhesives (The German company InnovationLab told us that photonic soldering could damage the ink close to the heated solder pad, while anisotropic adhesive methods did not always provide a reliable connection)

Sustainability

- How is 'cradle-to-cradle manufacturing', as stated on the website, applied in practise at TracXon and what are future plans?
- Is it possible to share insights from the ECOTRON project [1]?
- For example about how Holst Centre/TracXon what EoL/dismantling techniques for Hybrid Printed Electronics have the most potential?
- Does TracXon have experience using reversible adhesives that dissolve in heated water (such as by In2tec [2] or by SoluBoard [3] to separate components/conductive & dieelectric layers and the substrate?

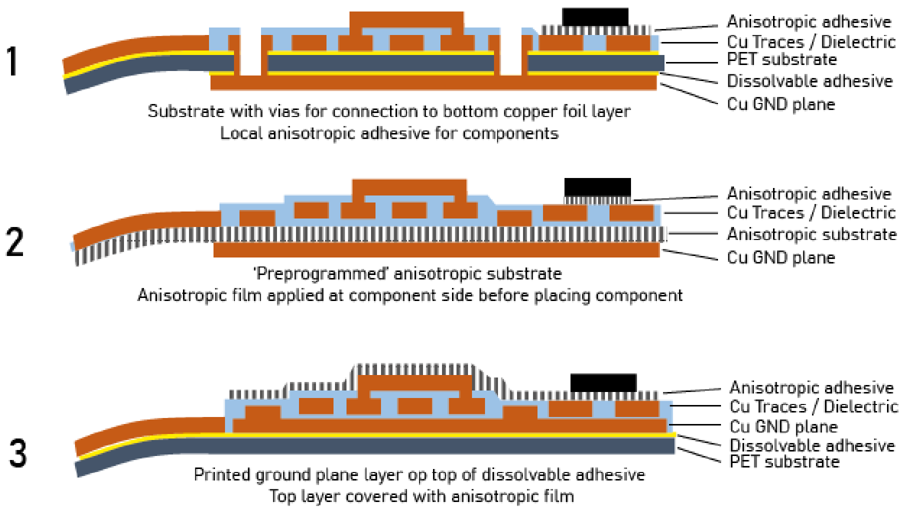
Investments

- What production method would you advice for producing 10,000 PCBs (for TRACK) per year.
- What prototyping options does TracXon have and what are the typical investment cost for a Hybrid Printed Electronics prototype?
- How accessible would the conversion of the current PCB design for the SODAQ hardware designers be? Do you use proprietary software for example?

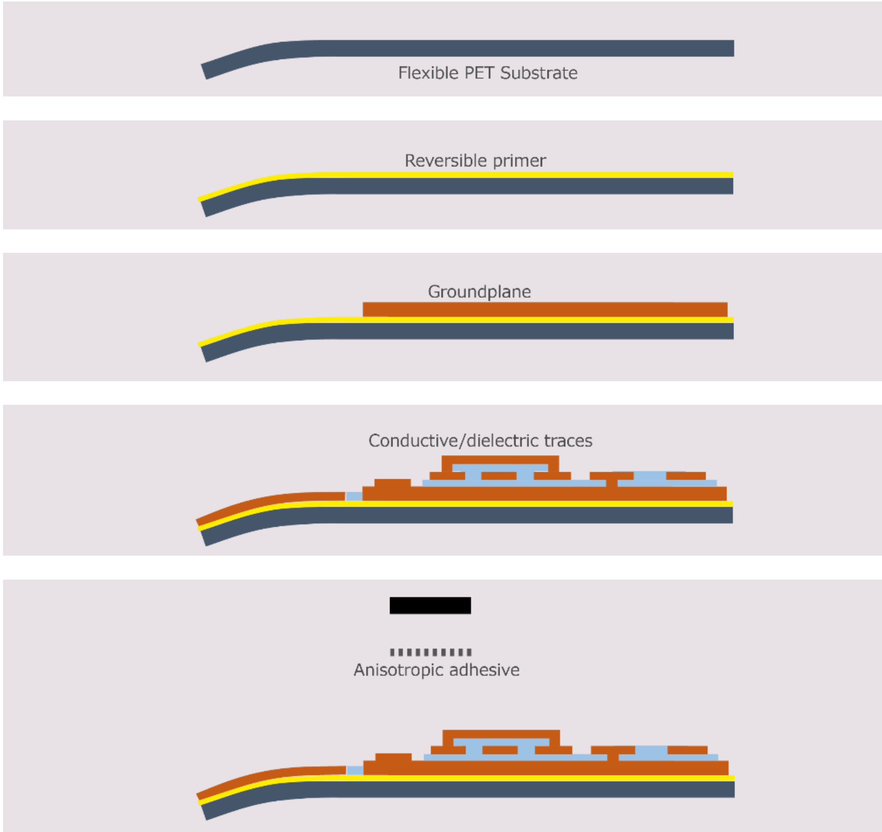
Appendix F6: TRACK Core FHE design for recycling

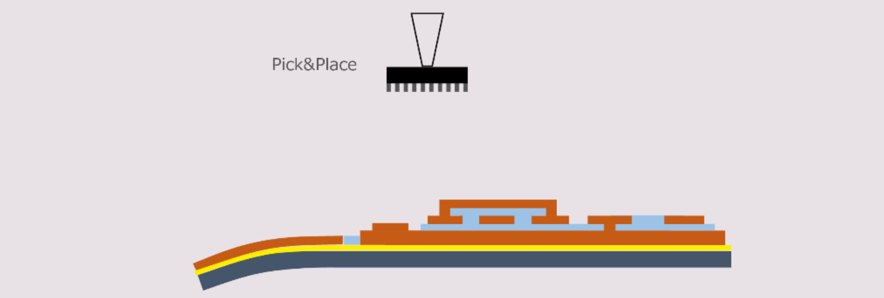
InnovationLab Core 2-layer FHE design example

TRACK Core 2-layer FHE options

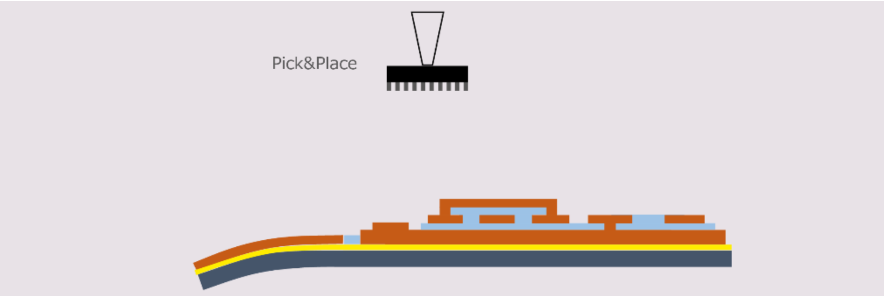


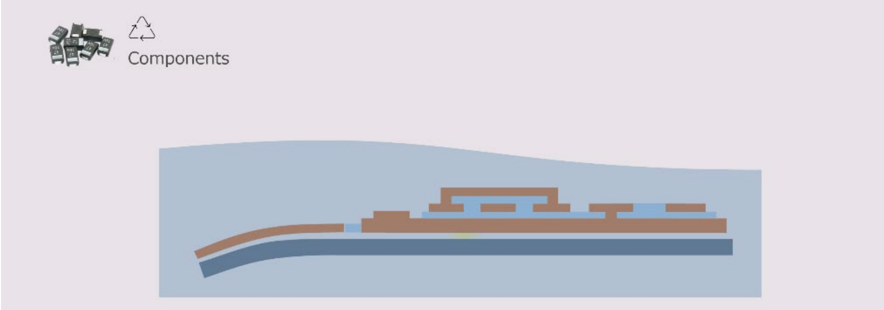
Core FHE assembly steps

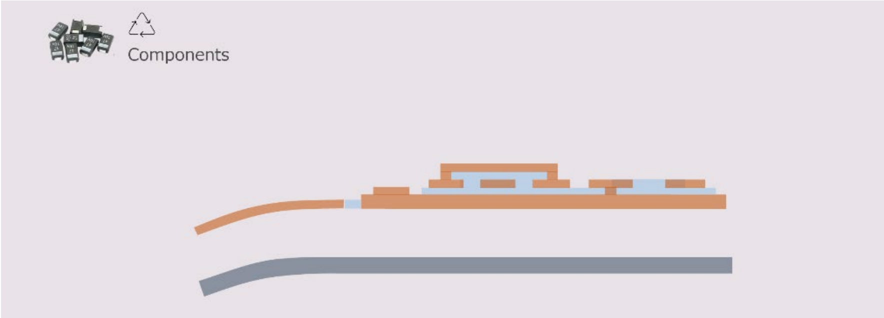




Core FHE disassembly steps

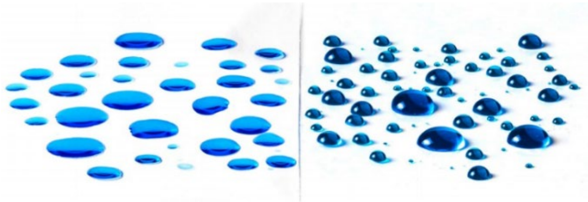






Appendix F7: Conformal coating sans PFAS

Conformal coating is a commonly applied technique to protect electronics from environmental factors such as water. However typical conformal coatings contain fluorinated substances (PFAS). One way to avoid PFAS while creating a hydrophobic surface is by applying nano-coatings such as a molecular plasma coating (Molecular Plasma Group, 2023)



Plasma hydrophobic treatment

Appendix G1: First Solar circular business model

Leading the industry by example: First Solar

The market leader in thin-film CdTe panels, First Solar, can be considered a circular pioneer in the PV industry. Since 2005 it has established a dedicated global take-back and recycling scheme and implemented a business model for closed loop recycling (see figure G1). To its customers First Solar offers a Recycling Service Agreement with 2-year termed renewable pricing or an on-demand service to cover the recycling costs.

By strategically investing in solutions that make their recycling process more efficient, receiving an increasing volume of end-of-life modules and rising waste disposal fees, the company expects that their recycling will eventually become the most cost-effective option compared to disposal. Finally First Solar claims to achieve an impressive closed-loop recycling percentage of over 90% for the semiconductors (First Solar, 2023). While current state-of-the-art open-loop PV recycling techniques cannot yet recover silicon of solar-grade that is necessary for reuse in PV manufacturing (Theelen, 2021).

By improving the recycling process even more one opportunity that First Solar is looking at is developing a mobile recycling plant. Using the mobile plant, end-of-life First Solar panels can be recycled on-site to produce new panels that can be installed again directly (CleanTechnica, 2018).

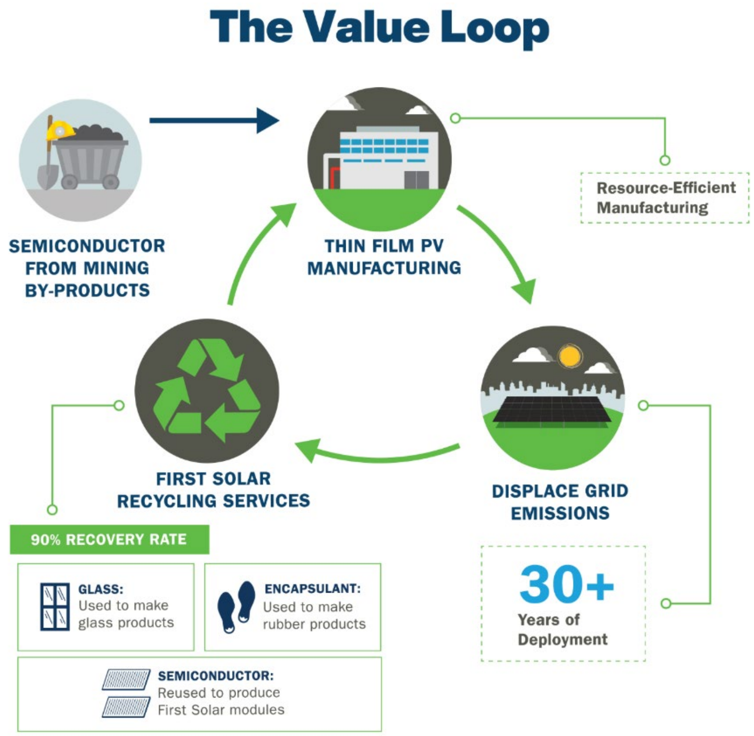


Figure G1: First Solar recycling loop

Appendix G2: Emerging PV technology

Organic Photovoltaic (OPV)

OPV cells are made out of conductive organic polymers or small molecules.

Dracula Technologies LAYER

French company Dracula technologies manufactures its LAYER cells using inkjet printing with bio-based conductive inks, specifically carbon-based materials. As the brand name suggests its Layer cells are aimed at indoor IoT products with a lifespan of up to 10 years (Dracula Technologies, 2023).

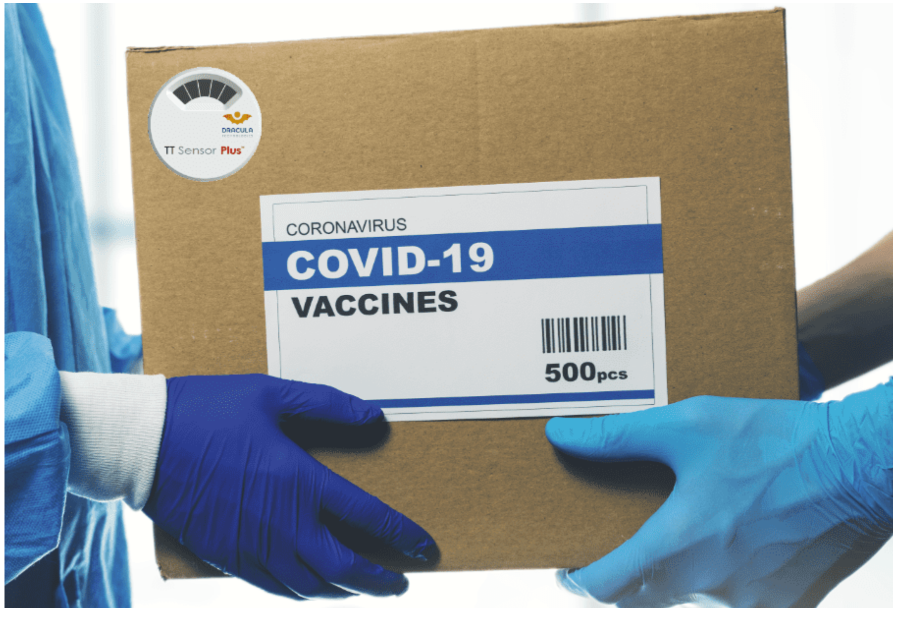


Figure G2: LAYER cell applied in temperature monitoring product

Epishine

Epishine solar cells (figure X) are non-toxic and encapsulated in recyclable plastics. The manufacturing process in Sweden is entirely based on various R2R printing techniques. Epishine claims that its current cell is particularly efficient in low-light environments and allows IoT products to generate energy in artificial lighting conditions such as offices. (EP&T Magazine, 2021). However it has recently announced the ambition to expand its OPV technology to suit outdoor applications as well. To this end Epishine has signed a licensing agreement with the industry leader ASCA, which is particularly known for its Building-Integrated OPV panels (Epishine, 2022). A first prototype achieves an efficiency of 8-9% (Epishine, 2023).

Figure G3: Ephine OPV cell evaluation kit

Dye-Sensitised Solar Cell (DSSC)

DSSC are made out of organic dye, inorganic semiconductors and an electrolyte. The photosensitive dye absorbs sunlight like the chlorophyll in green leaves (Wikipedia, 2023).

Exeger Powerfoyle

DSSCs typically consist of a transparent plate with a conductive indium tin oxide (ITO) layer on top of the layer with the dye that absorbs sunlight and releases electrons.

The Swedish company Exeger has found a way to shift the conductive layer from the top to inside the solar cell, increasing the amount of light reaching the dye absorber by 10-20%. Secondly, Exeger has replaced the expensive ITO electrode material with a special material that is both less expensive and has 1000 times higher conductivity (Exeger, 2021).

The result of the efficiency improvements is not stated but it might be more than current cell efficiencies of 15% outdoors and up to 34% indoors (Ren, 2023). Exegers DSSC are screen printed in a factory in central Stockholm powered by 100% renewable energy.

Exeger’s product is called Powerfoyle and is already used in some commercial IoT products such as dog trackers (figure G4a) with GPS and LTE-M connectivity (Spåra, 2023) and recently introduced as an add-on to Nordic’s Thingy:91 (figure G4b) (Exeger, 2023). It supports integration with Nordic nRF91 Series SiC that is powering the current TRACK line.

Figure G4 Powerfoyle applications (a) Spåra Hund dog tracker (b) Nordic Thingy:91 add-on

Perovskite Solar Cell (PSC)

PSCs are a relatively recent development in the PV industry. Their efficiency rose significantly from 6.5% in 2012 to about 24% in 2020 and this had a significant impact on the PV industry “Perovskites were a stick of dynamite dropped into the OPV world” (Service, 2022). For example the Australian PV company Greatcell transitioned from developing DSSC to PSC because the company became convinced that PSC will be superior over DSSC as well as OPV (Greatcellenergy, 2022). And although a lot of funding diverted from the development of new OPV technology goes into PSC, commercialization is still at very early stages with questions about durability and toxicity. For example the active perovskite layer is produced using lead, which is toxic. This means leaching during the lifetime of the panel must be avoided and also recycling has to be taken into account to prevent contaminating the environment. Meanwhile researchers obtained an efficiency of 19.3% for an OPV cell (Zhan, 2022). So while traditional PV efficiency has reached a plateau it looks like that it is yet to be seen which of these emerging technologies will be able to compete with silicon.

Saule Technologies
The Polish company Saule Technologies is the only one that has reached the stage of commercialization of PSC cells. The PSCs are inkjet printed using a R2R process. The efficiency in is around 15% outdoors (Babu, 2022), and up to 31% for indoor light conditions (Teixeira, 2022).

Although IoT products are one of the markets they are looking into, Saule Technologies’ first commercial applications range from sun blinds (outdoor) to shelf labels for retail (indoor).

Tandems
PSC can be used in tandem with Mono-SI to capture a broader spectrum of light and are therefore more efficient. However no tandem PV panels aimed at the IoT products are on the market yet.

Figure G5: Saule Technologies (a) Outdoor application (b) Supermarket shelf label

Appendix G3: PV panel encapsulation

To predict the durability of the PV panel in outdoor conditions it is important to find out when the PV encapsulation will fail. While the default substrate for printed electronics and thus also for emerging PV panels is PET, it is therefore important to check the durability under outdoor conditions. According to Voltaic their PET panel coating has a lifespan of just 2-3 years (see figure G6). This becomes an issue as the panel might experience delamination and compromise the water intrusion protection before the first intended lifecycle of the TRACK. The current coating of the PV panel is ETFE which would be more suited according to Voltaics data.

Coating	Expected Lifetime Outdoors (Years)*
Urethane	10+
ETFE	7+
Glass	10+
Glass with Frame	15+
PET	2-3

Figure G6: PV panel top layer materials compared

Appendix H1: Recycling strategies and materials

Closed-loop recycling

The hierarchy shows that the closed-loop recycling methods are the most preferred option. Closed-loop recycling promises to deliver plastics with good mechanical properties, while keeping the environmental footprint significantly below that of virgin plastic.

1.1 Closed-loop mechanical recycling

This type of mechanical recycling deals with plastics for which the composition is known as they are supplied by a recognized actor.

Advantages

- Because only one specific type of plastic is recycled, the material can be kept pure which results in a material that has essentially an identical composition as the original and could therefore theoretically be used in equivalent applications.

Opportunities for TRACK

The German company WIPAG has partnered with plastic supplier MOCOM to offer such a closed loop solution. WIPAG provides Recycling-as-a-Service or RaaS for WEEE plastic. In the RaaS customers will be able to tailor the recycling process to the specific requirements of their product (for an overview of the options see figure H1) (WIPAG, 2023). This way the company aims to offer a more efficient recycling process that should lead to a higher quality material as well as lower recycling cost. During the process the customer retains ownership of the material.

Challenges

- Given the low material volumes of the TRACK enclosure, in terms of number of units and weight per unit, the question for SODAQ is if such a dedicated recycling process could become economically viable. There might be ways to achieve the necessary economies of scale. For example by using a (more) standardized material recipe such that the recycling volume can be supplemented with plastic waste from partner companies that have adopted the same standardized recipe.
- Additionally the question of logistics needs to be addressed: how to acquire sufficient material volume for a recycling run. Currently, there is no policy for getting TRACKs back and even in the hypothetical case that all products are returned at some point, is total volume of material high enough?
- An other challenge for closed-loop mechanical recycling is the inevitable degradation of the material. While it is possible to effectively remove external contaminants such as paint, metal parts or dirt, internal additives that have been degraded over time, cannot be taken out. To compensate for the loss in material properties, compounding with virgin material and new additives is necessary to keep the material in the loop. Unfortunately non functional additives accumulate over multiple cycles, compensation cannot prevent that the material will exit the loop eventually.

input	material	1 Logistic Service	2 Shredding & De-Metallization	3 Density Separation	4 Paint Removal	5 Composite Separation	6 Electrostatic Separation	7 Repelletization	8 Compounding	9 Melt-Filtration	10 Drying	11 Homogenization	12 Packaging	13 Testing	14 Logistic Service	closed loop
Bumper post-industrial	PP+EPDM talcum	x	x		x			x	x	x	x		x	x	x	new Bumper

Figure H1: Modular recycling steps of WIPAG RaaS solution

1.2 Closed-loop dissolution purification

In a solvent-based recycling process only the target polymer is dissolved such that the remaining (solid) contaminants can be removed.

Advantages

- In contrast to mechanical recycling also internal additives can be filtered out, for example fillers such as fibres (Knappich, 2019) and toxic flame retardants (Anderson, 2021). Subsequently, the pure polymer is recovered after removing the solvent (see figure H2). By achieving a pure polymer as output, the material will stay in the loop for more cycles compared to mechanical recycling methods.

Opportunities for TRACK

The Dutch company Recycling Avenue, a TU Delft spin-off, is currently developing a pilot plant for closed-loop recycling of ABS plastic from WEEE. The company uses a dissolution purification recycling process that can produce recycled ABS with 75% less energy compared to virgin plastics (Recycling Avenue, 2023).

Challenges

- Solvent-based recycling technologies are still in upscaling phase which means the initial costs of the recyclate is still relatively high compared to mechanical recycling.
- The recycling potential is limited to a small number of plastics (e.g. ABS + PC recycling is not yet available).
- The purification waste stream is still a potential cause for sustainability issues as there is no clear EoL solution yet.

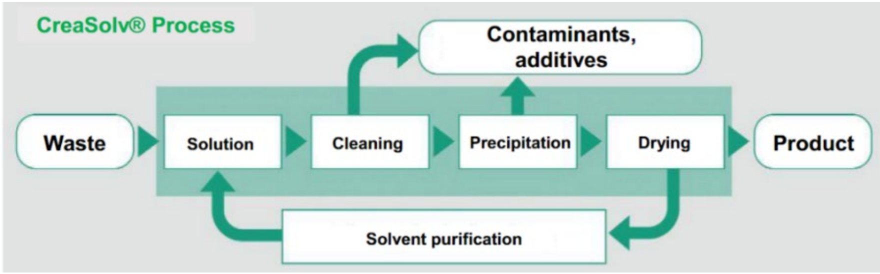


Figure H2: Typical example of solvent-based plastic recycling process

Open-loop recycling

Open-loop recycling would be the second most preferred route to obtain recycled plastics for the enclosure.

2.1 Open-loop mechanical recycling

In case a TRACK product is correctly disposed it will likely follow this route as it is the established recycling process for WEEE plastic waste. However the circularity assessment from chapter 3.4 shows that the current TRACK is not yet fully compatible with the recycling process leading to material getting lost.

Advantages

- Given that it is the established process, economies of scale make open-loop recycling more competitive with virgin grade material in terms of cost, while having the benefit of a significantly lower environmental footprint.
- A wide range of engineering plastics of various grades is available for the most commonly found types in WEEE plastic waste as shown in figure H3.
- Little to no adjustments in terms of business model is required.

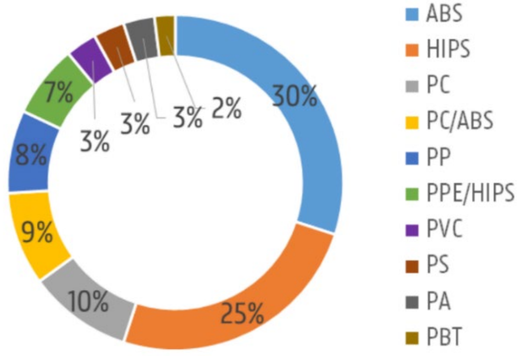


Figure H3: Typical WEEE plastic fraction (Achilias, 2015)

Opportunities for TRACK
There are numerous WEEE plastic recyclers that offer mechanically recycled PCR plastics that can be tailored-made to specification. One of the most well-known companies in the Netherlands is Coolrec which offers a 100% PCR ABS recyclate (Coolrec, 2022) or the Austrian company MGG which has a 100% PCR ABS-PC grade available (MGG, 2022).

Challenges

- The main concern of open-loop mechanically recycled plastic is the low quality of the recyclate. As open-loop recyclate is not reused in similar applications, a more appropriate term for this type of recycling would be downcycling.
  The low(er) quality can be attributed to the fact that the input material not only has been degraded during production and use phase, which is also the case for closed-loop, but the quality is reduced further during the recycling phase (see appendix H2) as the output is rarely a single type of polymer. Although the purity of the plastic improves every year, the sorting of the different types of plastic fractions remains complex. There a (too) many variables that are influencing the effectiveness of the separation process. For example a WEEE plastic fraction may be a blend of multiple polymers or they are contaminated or may contain a wide range of additives which all alter the physical properties of the material.
- Another challenge is the variation of the material composition between batches, as it is based on the input material mix of the recycled WEEE (PolyCE, 2022).
- A recent study from the UN shows that out of 13,000 chemicals identified in plastics, around 3,200 have one or more hazardous properties of concern (UNEP, 2023). So it happens that older WEEE products are recycled that still contain some of those harmful substances that are now restricted (e.g. Brominated Flame Retardants). Although these additives should be prevented from reuse in new products and disposed in a controlled way (Wäger, 2015), fractions may still end up being recycled. Tests need to be conducted by the recyclers to prove that harmful substances are either not present or at least that concentrations are within limits.

Chemical recycling

The third and last recycling strategy is chemical recycling. And while closed-loop recycling produces plastics with near virgin quality, it still has to be downcycled eventually. Chemical recycling methods promise to solve this by recycling the polymer in true sense of the word: back to its original virgin quality or better (upcycled).

3.1 Thermochemical recycling

As the name suggests heat is used in thermochemical recycling to either separate heavier and lighter molecules in pyrolysis or different (syn)gasses in gasification to produce bases materials similar to outputs from the oil gas industry.

Advantages

- Thermochemical recycling processes are mostly used for mixed plastic waste that is too contaminated or has a quality that is too low for other means of recycling.
- As the intermediate product is an oil or gas, the output does not necessarily have to be a plastic polymer, but the feedstock can serve a wider market for oil-derived chemicals and products.

Opportunities for TRACK

Currently thermochemical methods are not yet aimed at recycling suitable (engineering) plastics, but rather at low quality packaging waste (PE, PP).

Challenges

- Thermochemical methods can be considered a very crude way of recycling and require very high temperatures to break the plastics down. This means that they are significantly more energy intensive than the other recycling method, which not only makes it costly, but it also causes thermochemically (upcycled) plastics to generally have a higher footprint than virgin plastics.
- Furthermore, currently the processes are not able to remove certain additives (e.g. BFRs) (Anderson, 2021)
- The output yields are low; around 34% for gasification and 49% for pyrolysis (CE Delft, 2023).

3.2 Depolymerization

Depolymerisation is a more direct way of recycling than thermochemical recycling as it produces a monomer directly instead of via an intermediary product.

Advantages

- Breaking down the polymer to monomer level requires more energy than keeping the polymer intact, as in the case of primary and secondary recycling, however depolymerization requires far less energy than thermochemical recycling (see figure H4).
- The resulting polymers are of virgin level quality and are consequently easy to implement in production, as less or no trial and error is needed compared to other recycled grades and reliability of production process is easier to control.
- Virgin plastics provide more predictable mechanical behaviour during aging.

Opportunities for TRACK

3.2.1 Partial depolymerization

CuRe Technology uses a partial depolymerisation process – shortening the polymer chains just enough to allow removal of many impurities and to convert food grade PET into high quality rPET. CuRe claims that its process is less energy intensive than full depolymerisation and can produce rPET with 75% lower CO_2 emissions compared to virgin PET (CureTechnologies, 2023).

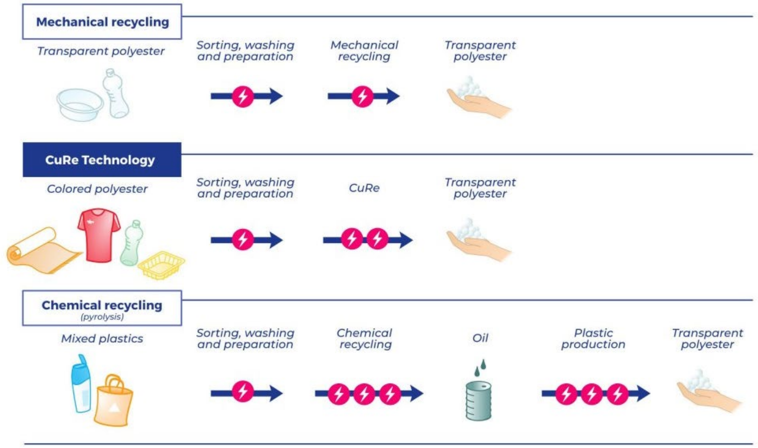


Figure H4: PET depolymerization compared to mechanical and (thermo)chemical recycling methods

3.2.2 Magnetic depolymerization (glycolysis-based)

Ioniqa, a spin-off from the TU/Eindhoven, has developed a catalytically accelerated reaction (using Magnetic Smart Materials) to degrade PET at 200 °C (Luxresearchinc, 2021). The process output is BHET, which is a monomer building block for PET (CE Delft, 2019).

3.2.3 Enzymatic depolymerization

The French company Carbios plans to produce an enzymatically depolymerized PET monomer (PTA), which can then be repolymerized to produce virgin PET (Tournier, 2020). As a first step Carbios has developed proprietary enzymes with the ability to break down certain polyesters, in particular PET. For PET a low temperature process (at 72°C) has been designed in which 98% of the input material is depolymerized within 24 hrs. In the future Carbios will expand its recycling expertise to other polymers such as polyamides and elastomers (Carbios, 2023).

DuraPET

Although PET is one of the main materials for more demanding packaging applications, it is generally not found in electronics enclosures. Apparently, the reason for this would be that the material has to be dried very thoroughly before it can be processed, which is considered challenging (Positive Plastics, 2022). This belief has not prevented the US based company Polyvisions from developing a PET variant for consumer electronics called DuraPET. It is a grafted PET copolymer material, which the company claims can be used as a drop-in replacement for durable ABS or ABS-PC parts that need to resist high impact and can be used for outdoor applications. Furthermore, DuraPET PCR is sourced for 91% from mechanically recycled PET bottles and can be recycled like standard PET, hereby closing the loop (depicted in figure H5) and making it compatible with the depolymerization recycling methods.

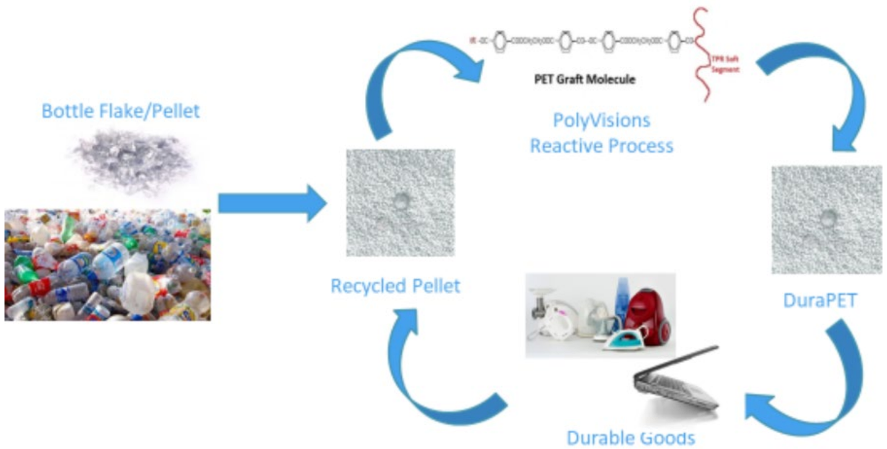


Figure H5: DuraPET PCR circular lifecycle

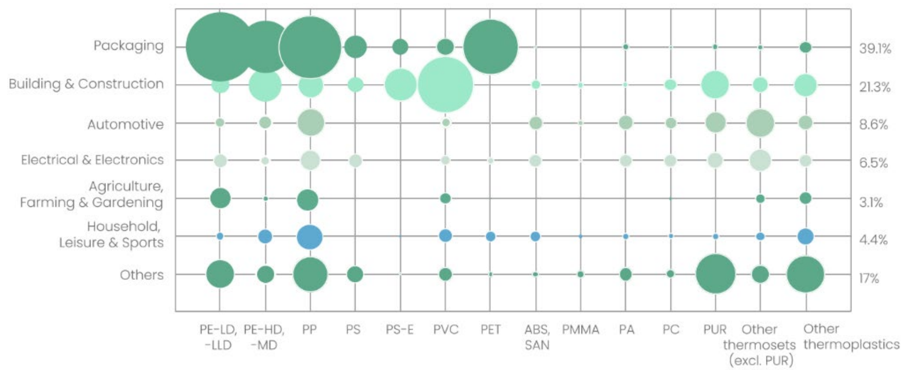


Figure H6: Plastic demand per application and type 2021 (PEMRG, 2022)

Challenges

- Depolymerization is only possible for certain types of polymers and research into the technologies is mainly aimed at the recycling of PET bottles and packaging, which is a very large market on its own (see figure H6) compared to other markets. These days there is a growing demand for new food-grade recycled PET, which drives the investment and scale up of PET depolymerization recycling plants (Luxresearchinc, 2021). Meanwhile depolymerization recycling infrastructure for other types of (engineering) plastic has yet to make its way out of the lab.

Appendix H2: Biobased plastics

A renewable alternative to recycled plastics are biobased plastics, derived from plants, bacteria fungi or algae biomass.

Advantages

- Plants remove CO_2 from the atmosphere as they grow and store the carbon in the form of biomass, which is consequently stored in the biobased material until it gets incinerated.
- Biobased drop-in variants of commonly applied plastics arguably have the most potential to replace virgin plastics on the short term as they have identical chemical composition. They can also be used as compounding materials for recycled plastics.
- Carbon taxes (EU ETS) will make carbon capturing materials more attractive in the future and increases the need to keep them (and the sequestered carbon) in the loop.

Opportunities for TRACK

Makrolon PC RE

The German plastic Covestro is a drop-in replacement for polycarbonate. It has a biobased content up to 72%, which is derived from 'biological waste and residue oils and fats' and is produced using renewable energy (Covestro, 2021). As it is a drop-in material, it can be recycled together with fossil-based PC.

PEF

PEF is a biobased alternative to PET, with a 60% higher modulus and strength than regular PET and has been developed by the Dutch company Avantium. The material is currently derived from grain or woodchips.
The company plans to offer the material from 2024 and is looking at ways to make PEF directly out of CO_2 (Brinkhof, 2023). Although PEF has a chemically different structure than PET, it can be recycled together with PET in limited quantities.

Primeflex

The German start-up company Made of Air claims to have created a CO_2 negative material called Primeflex. The main component is a biochar filler material that traps carbon, sequestered by trees, in a stable form. The biochar is created from locally sourced sawdust using a pyrolysis process without oxygen. The biochar filler is mixed with a binder made from sugar cane to form a material that can be processed like a thermoplastic; at least in products with wall thicknesses >1mm (Hahn, 2021). At EoL biochar can be used as soil enhancer while preventing rerelease of the carbon.

Challenges

- First generation biobased plastics compete with land use for food production and hereby indirectly contributes to deforestation (e.g. PLA derived from corn and sugarcane).
- Production of feedstock requires pesticides, fertiliser and irrigation (Lambert, 2017), which leads to local biodiversity loss and water stress
- The harvesting and processing of the raw material is still mainly done using fossil-based sources.
- The majority of biobased plastics are still niche materials, apart from PLA and some PA variants. This means that most biobased plastics will not be collected in a large enough volume (yet) and with enough demand to justify setting up a (closed-loop) recycling infrastructure, so not really a circular solution.
- The higher cost of drop-in alternatives compared to fossil-based virgin plastic due to higher raw material cost and equal economies of scale

Appendix H3: Polyvisions DuraPET

Figure H7: Application of DuraPET 0624 in Delll computer mouse

DuraPET 0624 NLP-OC		
1. Desiccant Dryer	YES	NO
2. Dryer Make		
3. Dryer Model #		
4. Ability to measure moisture % of Material	YES	NO
5. Current Material Type		
6. Current Material Model		
7. How many Cavities are in the tool?		
8. Cold Runner Tooling?		
9. Hot Runner Tooling?		
10. Mold Termperature to Mold Current Material?		

Figure H8: DuraPET moulding questionnaire for manufacturers

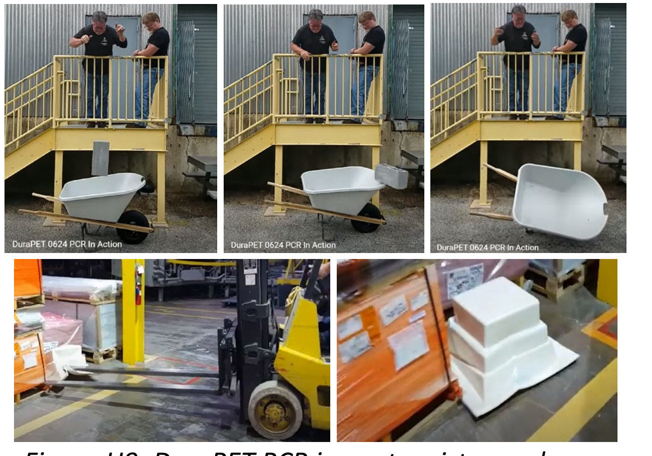


Figure H9: DuraPET PCR impact resistance demos

1. **Desiccant bed dryer is required.**
2. **Drying temperature for DuraPET PCR is 135- 145°C.**
3. **-40°C Dew point air recommended.**
4. **Typical drying time is 4 to 6 hours.**
5. **Maximum recommended moisture content is 0.02%.**

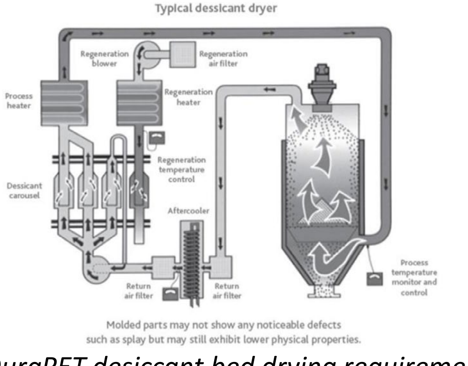


Figure H10: DuraPET desiccant bed drying requirement

Appendix H4: Interview Recycling Avenue

24 March 2023, Norbert Fraunholcz

Introduction
Today only 2-3% of plastic recyclate is applied in new products. Sand, metal powder and other contamination remaining after shredding is hard to remove successfully. Recyclate is mainly applied in low-value or non cosmetic, internal components.
Bigger problem than the recycling technology is the collection rate: only 55% in the Netherlands.

Closed-loop recycling
For closed-loop mechanical recycling, where appliances with homogeneous materials have to be put aside the number of times it can be reapplied in the same product category is about 2-3, in an optimistic scenario. This means we will not get there only with mechanical recycling.
With solvent -based recycling 6 times is the max before the material gets too degraded, but this all depends on the application naturally. For outdoor use this will be less.

Depolymerisation of PET
Depolymerization seems nice but there are serious issues yet to be tackled. For example the production capacity cannot be scaled up easily as it is not only a difficult chemical process, it also has a low yield and is financially risky.

Low yield
Depolymerization is based on chemical equilibrium this mean the efficiency is limited and part of the material will be lost.

Depolymerized PET cannot be sold as recycled content as the granulate has virgin quality this means that the price is directly coupled to the oil prices, which can fluctuate significantly. Solvent-based recycled plastics have a relatively stable price and it is easier to make agreements about securing supply in the future.

Ban on low grade plastics such as PET/polyester fibres
The expectation is that low grade plastics such as PP, PE and PET and polyester fibres will be banned in the future due to the microplastics issue and the fact that there is increasing evidence that exposure to plastic additives has negative effects on human health, such as disruption of hormones.
Biobased and biodegradable plastic such as PLA will take over the role of low-value plastics in packaging, but as everybody is jumping on the biobased materials, it will be hard to create enough leverage for a small company as SODAQ.
High quality engineering plastics on the other hand do have a future as they do not suffer from the microplastic issue. Furthermore the high quality of the material makes engineering plastics more attractive and valuable to keep in the loop.

Recycling Avenue Solvent-based recycling
Solvent-based recycling can filter out particles smaller than 1 micron. This means nearly all contaminants can be filtered out, only some pigments are smaller than 1 micron.
As a small producer of plastics it is hard to make an entry into the recycled plastic market. Currently Recycling Avenue will be able to produce ABS plastic at 25 kg/hour in its pilot plant situated in Chemelot in Geleen. In the future the solvent-based process can be scaled up to other engineering plastics such as PC.

Guidelines
The guidelines for solvent-based recycling are much less strict than for mechanical recycling. Solvent-based recycling can deal with fillers such as glass fibres, but the process would not be circular as the glass cannot be recovered cost-effectively. Metal parts such as inserts are not an issue and can be recovered for smelting.

TRACK 2024 as showcase for RE market introduction
The low production volume (600 kg/a) could make it a perfect fit with the current production volume aim of the RE pilot plant (see figure H11). Therefore RE proposes to use solvent-based recycled ABS as input material for the TRACK. TRACK Core 2024 could then function as a showcase for the potential of the recycling process to the market. Perhaps trials can be performed already for the current version.

Additives choice
It is important to study which additives are used as there are many that are toxic or have other negative environmental effects. Some can even be biodegradable after they have been removed from the polymer during the solvent-based process.

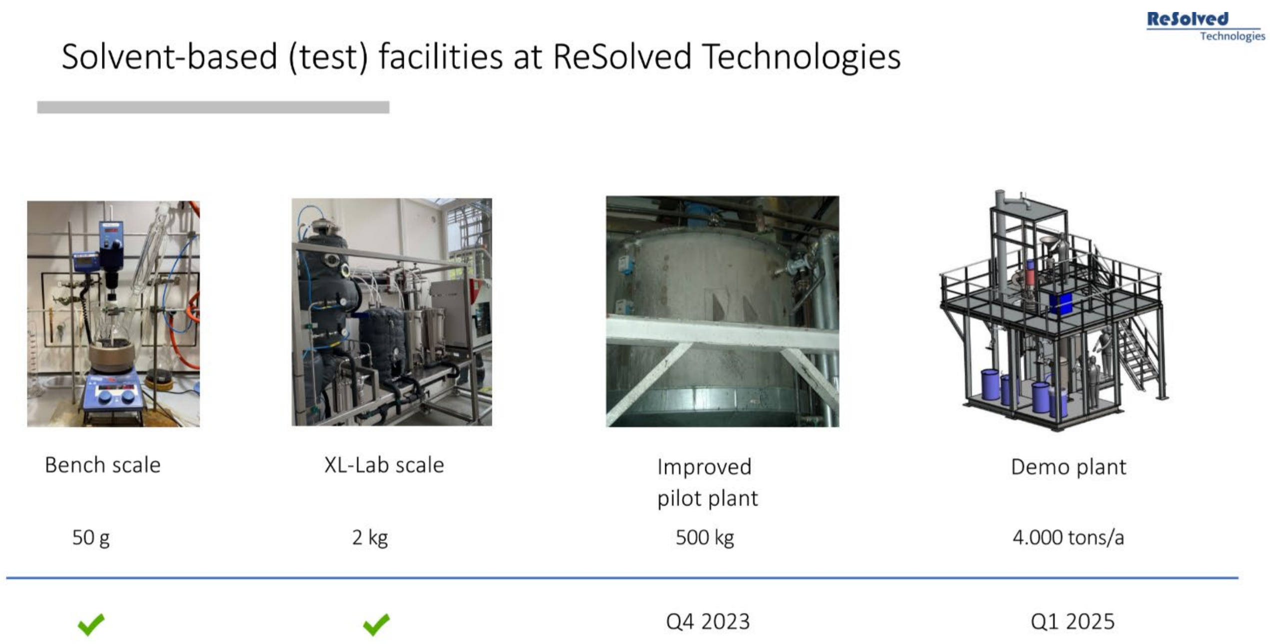


Figure H11: Solvent based recycling scale up timeline

Appendix H5: Marketing of recycled and biobased plastics

One of the reasons SODAQ (marketing department) is focused on the material is because it beliefs that it can be an effective way to communicate the intention of the product through its appearance, a marketing tool. This is a common method applied by companies that switch to recycled and biobased plastics in their products (Bos, 2022).

Capturing the value of imperfection

SODAQ is very much charmed by the recycling aesthetic that is commonly associated with mechanically recycled plastic, here labelled as 'artisanal pop'. The colourful and artisanal aesthetic is shown in the collage of figure H12. It has been introduced to the wider public by the Precious Plastic movement which started experimenting with packaging waste to create a material expression that embraces the imperfection of mixed plastic waste. Ever since, it has been adopted by furniture companies and recently also in electronics (Fairphone 4) and automotive interiors (Volvo EX30).

Connecting the artificial to the natural

A second theme that can clearly be identified is the connection that might sound absurd at first: bringing nature to something as man-made as plastic. Yes, biobased materials are from natural origin but the marketing departments do not seem to mind: recycled plastics are considered 'green' too of course. Customers are faced with products that seem to differentiate themselves solely through a paint job and *au naturelle* appearance (see collage of figure H13). For this muted/pastel colours are applied that are either a choice between leaf green, earth tones or sea green.

Figure H12: collage of 'artisanal pop' plastic aesthetic

Figure H13: collage of 'au naturelle' plastic aesthetic

Appendix H6: SODAQ Brand identity guidelines

Colour, Material & Finish

Colour, Material & Finish or CMF is a very important step in accentuating the product form through the use of colours which could appeal to the users, are trending or could further boost a certain goal, in this case, the concept of sustainability through nature.

Colour

"Products such as the ones that SODAQ wishes to create would benefit from colours that draw the perception of nature and long-lasting appeal from looking at them which is why earthy and pastel tones are a good combination with such organic forms."

Material

"PLA based bioplastics are known to be eco-friendly while also being able to undergo an industry adopted process such as injection moulding. Recycled plastics are also an option as they create a natural speckled look in the material owing to the addition of used plastic back into the mix such as in the case of Durat or ecothylene. A more controlled result can be achieved through spray painting."

Finish

"High-gloss finishes can be seen in high-end products as the reflectivity and shine add to the premium feel, these are also easy to clean and hide scratches well.

Matte finishes create a sophisticated feel in the product but are prone to dirt collecting on it and difficult to clean."

Figure H14: SODAQs design language

Appendix I1: Disassembly of Urbanista Phoenix wireless earphones

Figure I1: Sunny marketing image "Inspired by the breath-taking desert scenery of one of the sunniest places on earth" (Urbanista, 2022)

Figure I2: Notably hard to open without damage due to snap fits on four sides; no flexible sealing of PV panel, but pressed to the outer enclosure through the wedge design

Figure I3: (a) No 'direct access' design due to inner enclosure sandwich design; inner structural part necessary for provide support to the flexible PV panel on one side and button and LEDs on the other. (b) unscrewing the enclosure parts unlocks the earphone charging cradle part. LiPo battery is fixated using double sided adhesive tape.

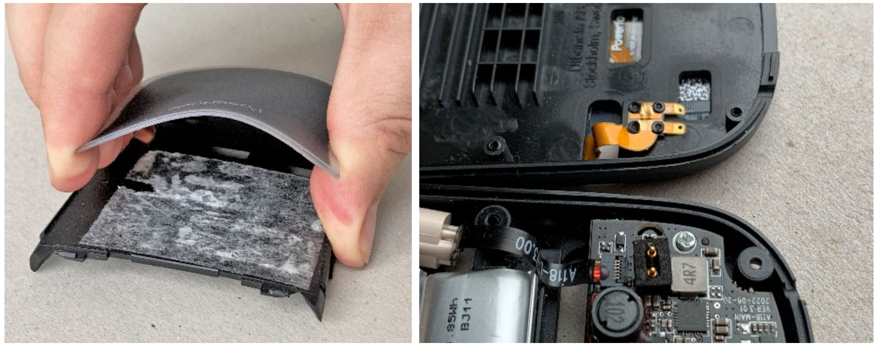


Figure I4: (a) Flexible PV panel attached to inner housing using double sided adhesive tape (b) PV panel attached using flex cable and PoGo pins to prevent damage to cables and connectors during assembly; spring-loaded PoGo pins put under tension by four self-tapping screws

Appendix I2: Disassembly of Xeelas S2 asset tracker

Figure I5: Attached to asset with external sensor connected.

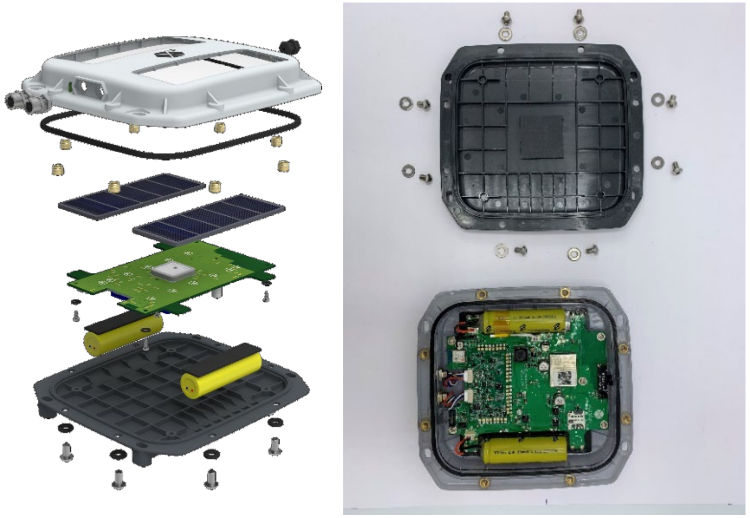


Figure I6: (a) Exploded of components; (b) Opening provides direct access to electronics

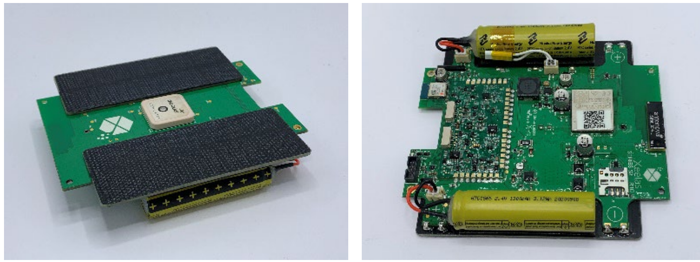


Figure I7: (a) Clumping of electronic components: PV panel is soldered to main PCBA and (b) Li-ion batteries are fixed using adhesive tape

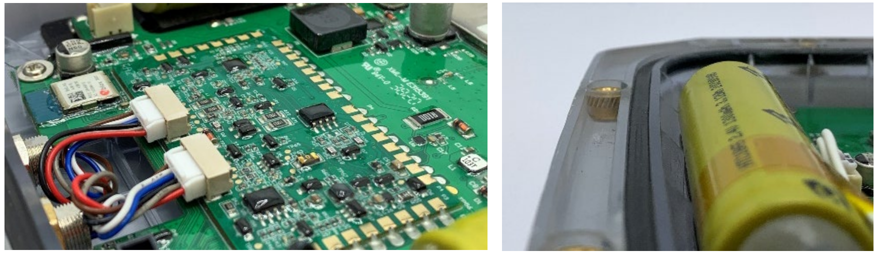


Figure I8: (a) Conformable coating for waterproofing PCBA with interesting PCB stacking design. (b) Rubber seal and inserts for opening

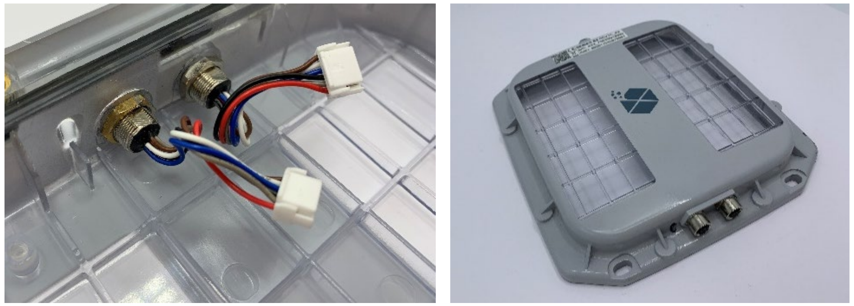


Figure I9: (a) Screw in connectors with potting for waterproofing of cables; (b) Transparent housing for PV panel shielding, covered with coat of paint

Appendix J: TRACK Core IP67 test report

Test 1

Sealing material test 1

Recommended for the application by sealing/gasket suppliers (Sealution, Techniparts):

- Series production: VMQ silicone (injection moulded)
- Prototype: EPDM foam (die cut from sheet)

Figure J1: Die cut seal

PARAMETER	FUNCTION
MATERIAL	EPDM foam with adhesive side (die cut from sheet by Techniparts)
THICKNESS	1 mm
SEAL THICKNESS IN CORE CAD MODEL	0.8 mm
SHORE VALUE	40B
UV RESISTANT	YES

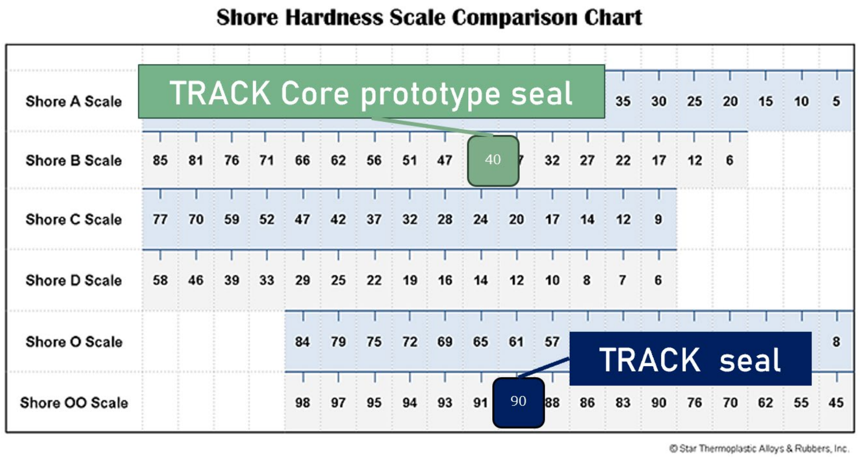
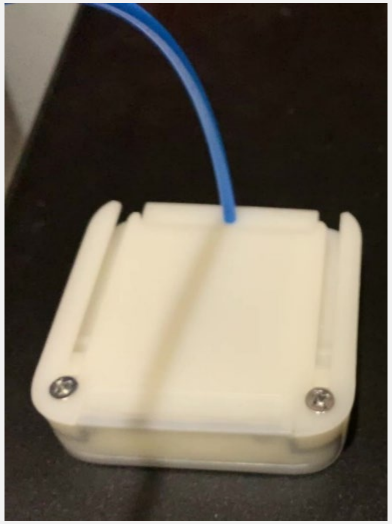


Figure J2: Shore value of Core prototype seal compared to current TRACK seal shows it has only a slightly higher hardness

TRACK Core enclosure prototype

To mimic the properties of the injection moulded enclosure parts 3D printing and CNC milling were explored.
CNC milling would not be able to achieve the fine detail of the drawer part that is required for reliable sealing. The drawer has some sharp corners at the rounded off edges that are impossible to reach with the CNC drill bit.
Together with the Center of Design for Advanced Manufacturing of the TU Delft, SLS printing in combination with a vapour polish after treatment was chosen as the best option. The vapour polish will ‘fuse’ the layers of the 3D print together, hereby not only creating a solid air- and watertight shell, but also a smooth surface. The smooth surface is required for reliable sealing performance. The material of the enclosure is PA-11 (a biobased thermoplastic) and printed by the Dutch company Oceanz.

Sealing variants

EXTERIOR MOUNTING	INTERIOR MOUNTING
 	
▪ FDM printed Ultimaker Tough PLA exterior bracket ▪ Mounted to surface for sealing with nuts and bolts	▪ Inserts and screws for sealing

Insights test 1 mm thickness seal
0.2 mm compression on 1 mm rubber turned out to be too little therefore two layers of the EPDM foam were pasted on top of each other to get a **seal of 2 mm (1mm + 1mm) thickness**

Results of test 1

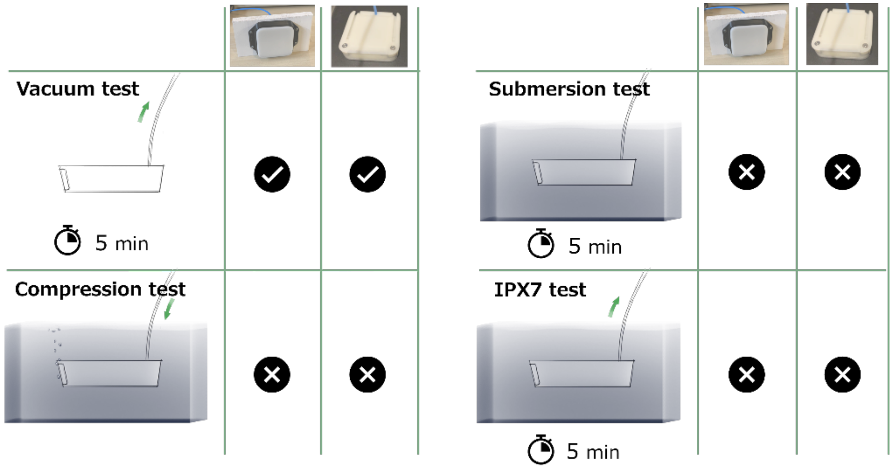


Figure J3: overview of tests and results of test 1 with 1+1 mm seal

Vacuum test
Both variants seem to be air tight on the basis of a vacuum test at 0.1 bar, with a only a small pressure loss after 5 minutes.

Compression test
Interestingly, the bubble test (housing under water with an air pressure of +0.1 bar) shows that the mounting variant with a exterior bracket allows virtually no air to escape (figure J4a), while with interior mounting variant bubbles come out continuously (figure J4b). In both cases the bubbles originate from the top edge of the lid.

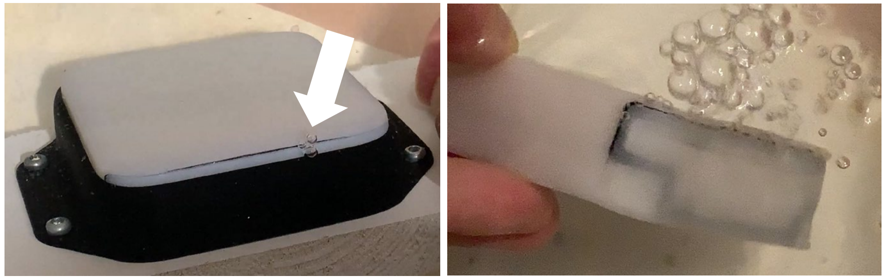


Figure J4: (a) bubble appearing from exterior mounting variant (b) continuous stream of bubbles in interior mounting variant

Submersion test

The exterior mounting variant makes significantly less water with the thicker seal, but still too much to justify further testing.
The interior mounting variant remains almost dry after 5 minutes submersion under water, but small water droplets are visible at the rail of the drawer (figure J5). Not tested for more than 5 minutes.

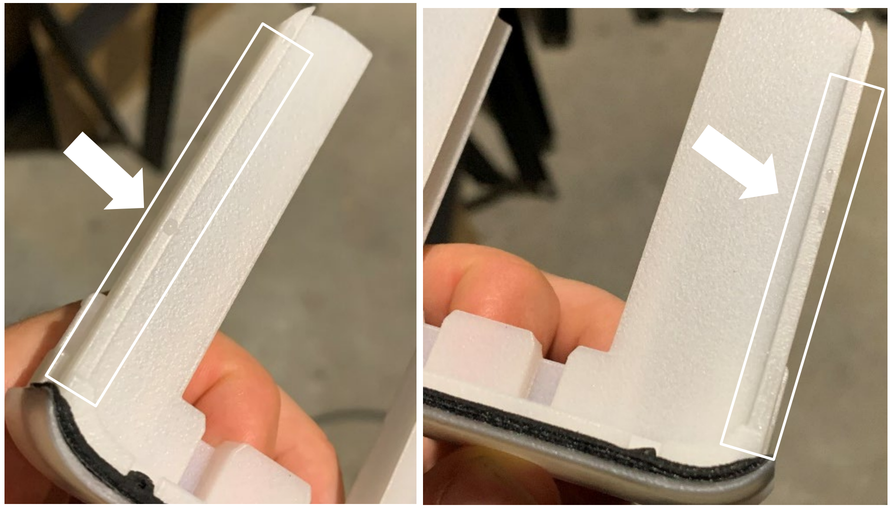


Figure J5: Droplets visible on rail on both sides of drawer after submersion

Conclusion test 1

- Housing appears to be sufficiently airtight and waterproof and surface quality is smooth enough for a meaningful test for the degree of sealing with cellular rubber
- Self-adhesive rubber is difficult to place neatly in places where water intrudes as it sticks to the enclosure surfaces
- Bubbles emerge from a different spot (top) than where the water seems to enter (more on the side near the rail). Compression testing therefore has little added value to pinpoint the leak.
- SLS printed enclosure is too deformed to perform further meaningful tests with the exterior mounting bracket (figure J6a). An alternative to the bracket could possibly still be done with something that does not rely on an exact shape fit for clamping, such as a belt or strap.
- Plastic deformation of the enclosure close to the mounting point after tightening the screw for the interior mounting variant (figure J6b).
- Mounting bracket could cause an issue by pulling the drawer forward when mounted (figure J7)

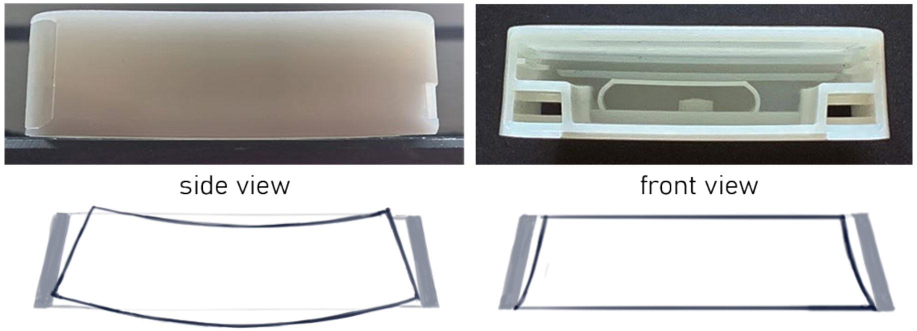


Figure J6: Implications of deformed enclosure resulting from (a) SLS 3D printing and (b) plastic deformation on contact surface of exterior mounting bracket and thus sealing performance

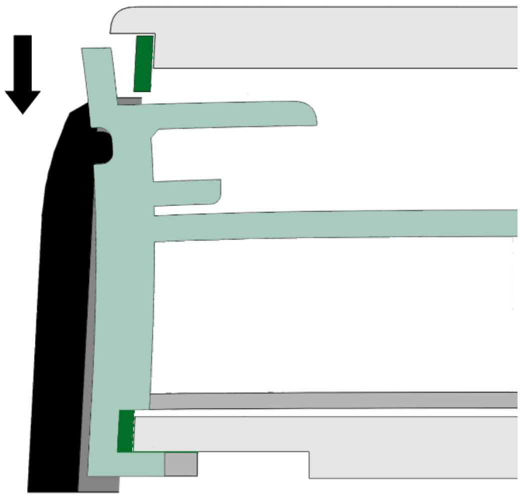


Figure J7: Potential inverse sealing effect of external mounting bracket at the drawer top

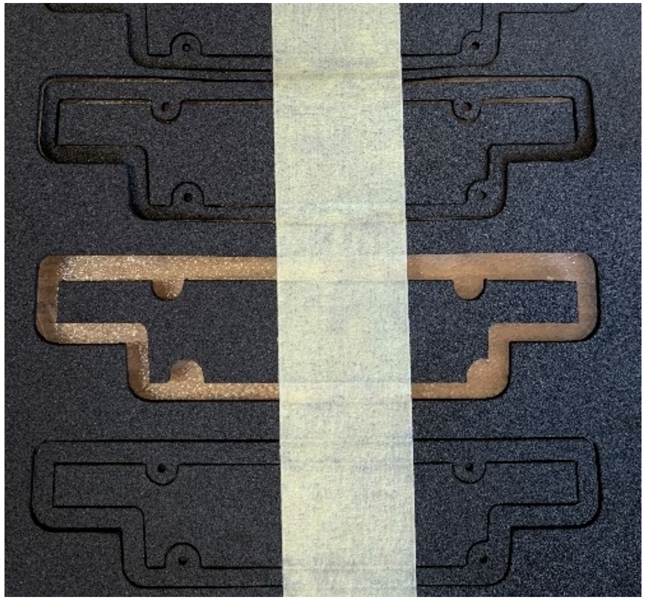


Figure J8: From the various designs the best fitting one was used for the test

Test 2

Sealing material test 2

Some improvements to the design of the seal were made, most notably the width of the foam seal at the outer sides was extended to counter the leakage issue at the rails. Unfortunately Techniparts did not respond in time to the request for a new seal. Therefore the decision was made to produce the new seals by laser cutting them from a 2mm EVA foam sheet at the TU Delft PMB instead.

PARAMETER	FUNCTION
MATERIAL	EVA foam without adhesive side (laser cut from sheet by PMB)
THICKNESS	2 mm
SEAL THICKNESS IN CORE CAD MODEL	0.8 mm
SHORE VALUE	> 40B
UV RESISTANT	YES

Results of test 2

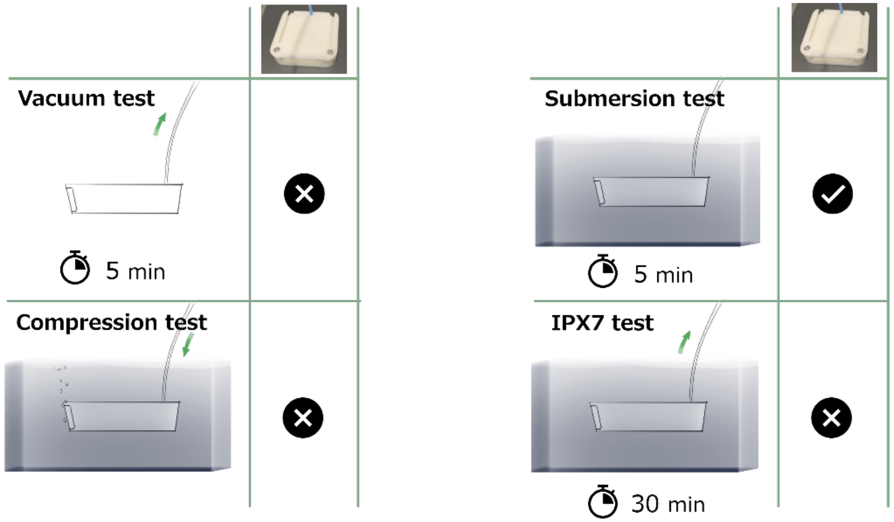


Figure J9: overview of tests and results of test 2 with interior mount and 2 mm seal

Vacuum test

The new sealing seems less airtight than in the previous test, however this can be attributed to the fact that the seal is still completely dry while the vacuum test of test 1 was performed after a first submersion test

Submersion test

After 5 minutes of submersion the prototype remains dry, even at the rail (figure J10a and J11b)

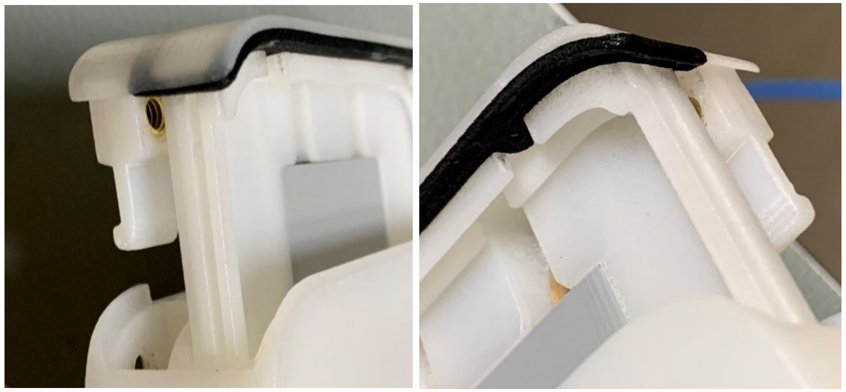


Figure J10: (a) drawer rail left (b) drawer rail right

IPX7 test

Test with 0.1 bar vacuum (to simulate a 1m water column) for half an hour (IPX7 test conditions). After opening several drops remain at the position of the rail (figure J11a and J11b).

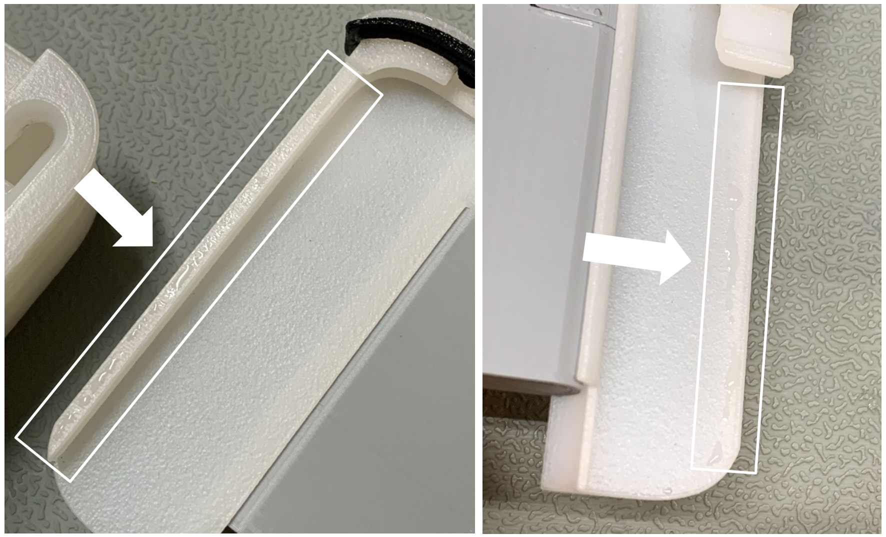


Figure J11: (a) drawer rail top left (b) drawer bottom left

Conclusion

Closer inspection of the seal at the rail edge shows that the enclosure leaves an indentation on the rubber. The cut out of the drawer rail causes that of the seal is not pressed against a even surface, this likely creates an gap for the water to enter (Figure J12). To solve this, the extruded cut made for the rail should become less deep such that the rubber will be pressed against a even surface, hereby eliminating the indentation.

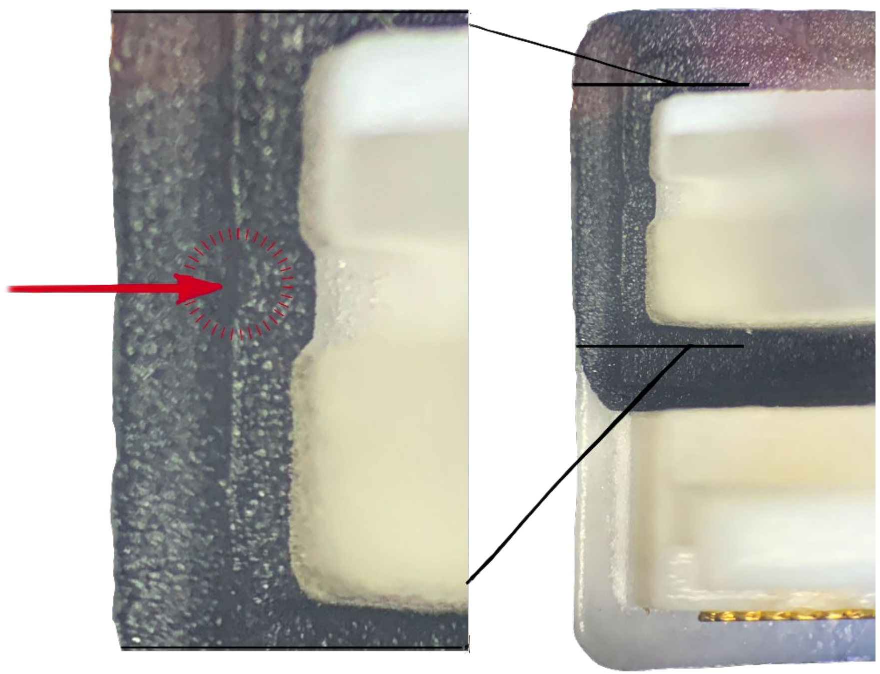


Figure J12: Potential cause of leak a the rail

Appendix K: Project brief

Blueprint for a 'World friendly' Track product line

project title

Please state the title of your graduation project (above) and the start date and end date (below). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

start date 15 - 11 - 2022

15 - 06 - 2023 end date

INTRODUCTION **

Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

The market for IoT devices is currently growing exponentially. While the application of IoT has the potential for companies and governments to make their processes more resource efficient and enable them to implement circular business models, the production and usage of current IoT devices also has a very negative sustainable impact. A back-on-the envelope calculation for the discarded batteries of the 100 billion connected smart devices in 2050 would fill approximately 500 Olympic-sized swimming pools, made the employees of the IoT company SODAQ realize that with the products in their current form this market can never be sustainable on the long term. So this year SODAQ committed themselves to take environmental and social responsibility and rebranded itself as a 'World friendly IoT' company. After phasing out batteries and implementing a more energy-efficient communication protocol for their current SODAQ Track product line, the focus for the next iteration is now on decreasing the CO2 footprint of their housing. A LCA for the previous Track product (with battery) proved that this is very much needed: the plastic housing contributed to 70% of the total CO2 footprint of the product.

SODAQ

SODAQ is a relatively small (45 employees) engineering company in the B2B market for GPS-trackers and environmental sensing devices. Their core competency is the development of very energy-efficient IoT electronics, but they also have an in-house design department experienced with producing plastic housings for long-term outdoor use worldwide. SODAQs teams mostly work on a project to project basis, meaning that the requirements of the design are largely dependent on the demands and (linear) business model choices of SODAQs clients. On the other hand the company is responsible for both developing all hardware and software. This gives them full control over the product and provides the designers more flexibility in changing the product's architecture. Lastly, given the small size of the company (in terms of people as well as space), the amount of shipped products and the slim margins, it is not considered to be realistic to set up an in-house refurbishment and remanufacturing business at the moment.

Clients (e.g. Bayer, Van Oort)

SODAQ wants to offers its clients a sustainable solution and while these companies might be interested in longer lasting products, manufactured with a lower CO2 footprint, they might not be familiar with the other opportunities of the circular economy. As IoT devices tend to be relatively inexpensive and the technological innovation in this relatively young market is going fast, the incentive to set up a dedicated maintenance program themselves is low. Broken devices are simply replaced with newer models.

End user

SODAQs is in the B2B market, so it has no direct relation to the end user. But he/she has the vital task of being responsible for the product during its functional life and hence the state the product ends up in the e-waste stream.

Manufacturers

SODAQs (Chinese) manufacturer refused to replace virgin plastics with recycled content in the current Track product. This shows that manufacturers can be quite resististant to applying new (recycled) materials. However examples of electronic devices produced with 100% PCR plastic show that producing thin walled consumer products (in Europe) is very much possible in case some specific guidelines are followed and the right granulate is chosen.

WEEE waste recycling companies and material suppliers

Luckily some recycling companies already take the leap and invest in equipment and additional treatment steps to offer recycled material of increasingly higher quality. Although manufacturers are not (yet) rewarded for their efforts to make the recycling easier, it is important for companies such as SODAQ to take responsibility for keeping materials in the loop, such that these materials can be used in future products such as a next gen Track.

space available for images / figures on next page

image / figure 1: Rendering of the current SODAQ TRACK line (excluding the BLE version)

image / figure 2: SODAQs areas of focus to become a 'World-friendly' IoT company

PROBLEM DEFINITION **

Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

The new 'World friendly' Track product line should be designed for a circular business model such that the CO2 impact will be lowered compared to the current generation. For the redesign the focus should be on the mechanical parts of the product. The main question that project tries to answer is: How can the SODAQ TRACK line be redesigned to fit in a circular business model?

To understand what components and materials should be the focus of redesign an impact assesssment is done.
RQ1: What is the current impact of the product and its components?
1.1: Which components and which life stages have the highest potential for impact reduction through a redesign?
1.2: What is the highest potential impact reduction for the housing components specifically?
To provide an insight into what parts of the product are adhering to circular principles already and what parts are not, the track is scored on the relevant criteria.
RQ2: What are the relevant scoring criteria to assess the TRACK on the principles of circular design and determine how circular the TRACK in its current form already is?
Next, the most relevant circular strategies are chosen based on the highest potential
RQ3: What circular strategies have the highest potential for reducing CO2 impact?
3.1: Which components, failure modes or company strategies are likely to limit the maximum lifetime of the product?
3.2: How to assess the component state and decide on their eligibility for reuse cycles?
3.3: What circular business model would enable SODAQ to bring circular products to the market the most quickly?
3.4: What are specific circular opportunities for a traceable product?
Finally, the product is redesigned according to the chosen principles.
RQ4: How should the product design be adapted to meet the identified circular strategies?
4.1 How can the redesign be validated to match the scoring criteria identified in RQ2?

ASSIGNMENT **

State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in "problem definition". Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, ... In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

As an end result I will create a blueprint for the SODAQ Track product line that adheres to the principles of circular products design without compromises. To demonstrate what a future implementation could be I will construct an alpha prototype of the bestseller out of the product line: the Track Solar and a road map to make this a reality.

The final product will be a physical redesign of the Track Solar. The redesign will be a near production ready show model that can inspire both SODAQ and its clients what the term 'world friendly' stands for and what circularity means in terms of product design. To highlight the feasibility of the design, the model is tested for the most important durability requirements such as achieving an IP67 rating and the relevant structural integrity tests. Furthermore the viability is shown based on assembly trials and a technical data package (technical drawings etc). If possible a mechanical liberation test at a recycling plant can provide real life insight how well the design performs at the end of its life.

In the accompanying road map the next steps to take the proposed product to the market are documented. This means: what material sources can be used, where and by whom the parts can be manufactured and where and by whom the product can be assembled and how the the product can be repaired, refurbished and upgraded in the future. Futhermore this proposal gives an indication how a circular business model could look like and how this could change the relationship with SODAQs clients as they are need closer cooperation even after the product has shipped. Finally other cooperations with third parties are proposed to make the transition easier for SMEs such as SODAQ.

PLANNING AND APPROACH **

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any, for instance because of holidays or parallel activities.

start date 15 - 11 - 2022 | 15 - 6 - 2023 end date

The project is structured in 4 phases and a documentation phase. I will work 4 days a week as I am working on an other project for the water filtration company one day a week.

Setting the scene
I start with getting familiar with the project context and the requirements of the current Track product line. At the end of the research I want to conclude by giving the TRACK a circularity score and recommendations for the next phase.

Exploring circular redesign strategies
Here I want to apply my knowledge of circular product design to improve the TRACK for the most relevant circular design strategies. This is where I can divert by exploring ideas for the circular loops and this process is based on circular product design principles. I structured the process following a research by design method such that I can make quick iterations and find out quickly what important tensions there exist and which ideas might create interesting design opportunities . Succesful solutions can be combined such that circa 3 design directions are formed from which the most promising concept can be chosen.

Materializing the redesign
Here the materialization of the most promising concept takes shape by starting off small scale material property testing up to a full product production trial.

Validating the redesign
Validate whether the redesign not only meets the circular criteria but also meets the current product requirements.

MOTIVATION AND PERSONAL AMBITIONS

Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... Stick to no more than five ambitions.

The sustainability courses teached on the TU Delft focus very much on the system level: what are good circular business models? As an IPD master student I have always been curious what the theory about circular product design means in the real world at the product level. This project provides the opportunity to experience this first hand.

I want to get experience about the final stages of the design process and what the specific challenges are and how it can inform early design decisions about form freedom and material choice.

Get a feel for the developments present in the field of manufacturing with more sustainable materials (outside of the faculty). Are recycled plastics really the answer for more sustainable products or do we need new solutions? And what challenges do SMEs have in the transitioning towards more sustainably produced products.

During previous projects I became more and more interested in developing electronic products. In this project I can get experience with what requirements a production ready electronic product means, such as how PCB are designed and what elements influences the performance.

As an IPD student I would like to apply more technical skills in my project such as product simulations and tests.