Master Thesis

InnoEnergy MSc Renewable Energy
Master of Energy Engineering

Sustainable energy solutions for stand-alone IoT devices

Technical, environmental and economic assessment
to find alternative tecnologies to power
RecySmart and Single Sensor IoT devices

MEMORY

Author: Benjamín Varese
Director: Cristóbal Voz Sánchez
Call: Pròrroga

Escola Tècnica Superior
d'Enginyeria Industrial de Barcelona

ACKNOWLEDGEMENT

To begin with, I would like to thank my parents, always encouraging me since my first steps in this life until today, with tireless belief in my capabilities. Also, I am grateful to my brother and sister with their families, my friends and my couple for their joyful support in all the process of my studies. Finally, to all my companions during my studies, with which I was able to share thoughts and classess but better than that, is that I have got friends that I will never forget.

Second, I would like to mention the great support that Recircula Solutions has given me both for this Master Thesis and with my current job position. I am totally sure that I have found not only excellent professionals but also friends in my companions. Special thanks particularly to Jordi Berguinzo for the continuous support and truth on my skills and personality.

More, I should thank InnoEnergy and the the host universities of my Master studies for opening the doors to the incredible experience of my studies: KTH Royal Institute of Technology (Sweden), Universitat Politècnica de Catalunya (Spain), ESADE Business School (Spain). To InnoEnergy I would like to give a special mention for the life-changing opportunity I was gifted with. Last, I had the pleasure to work at InnoEnergy's Headquarters in Iberia and became aware that behind all the efforts towards shifting to a more sustainable world, the most valuable of all is the people working hard day by day for the same goal.

In addition, the Universidad de Buenos Aires deserves all of my appreciations, with all its flaws and virtues, for having prepared me through seven tough years to overcome whatever challenge is in front of me, even when the landscape, method and culture are different.

Finally, I must thank my supervisor Farzin Golzar for his dinamic and agile mentoring while also understanding my needs, and to the examiner of this Master Thesis, Prof. Dilip Kathiwada for his rigorous and highly valuable feedback to make me focus my approach towards scientific research.

ABSTRACT

This work is intended to provide a high-level assessment of energy solutions to power Internet of Things (IoT) devices. The criteria for the evaluation are technical, environmental, and economic. Different technologies will be covered with support from published scientific research and the market existing solutions. The analysis will be done for a particular case study but the followed steps should serve for others looking to tackle the same issue. The intended outcome is a preselection of one or more alternatives to improve the power supply of the case study devices according to the mentioned criteria. The selection of alternatives will also include a guideline on which developments to follow and the main reasons to do so. The work is done from a business and practical perspective, meaning that after taking a first decision thanks to this work or the steps followed on it, the R&D departments of the ICT (Information and communications technologies) companies applying the methodology should then study the selected alternatives in a deeper technical analysis. In the conclusions, general next steps to carry out the development will be established. Throughout the work, it is demonstrated that there is not one single combination of technologies that is the best in all aspects, for all weathers and locations, and all applications. On the contrary, the assessment reveals how different devices and conditions affect the decision on which is the most suitable decision. In addition, there is not any alternative that has the best ranking in all aspects, as there are always technical, environmental and economical compromises. As for the specific assessment for the current status of RecySmart device (the first device of the case study), it is recommendable to follow the development towards solar photovoltaic panels in combination with Li-ion or LiPo rechargeable batteries to remove the current primary cells. The selected alternative will involve some developments but has the capability of reducing the cost of the device's power supply by 48.9% in a 5 years period, while reducing the overall environmental impact. Thanks to the use of a solar panel and secondary cells, it is possible to eliminate 92.1% of the lithium batteries used (moving from primary to secondary cells) and ensuring the autonomy of the device. Finally, for the Single Sensor studied (the second device of the case study), the recommendation is different to the one of RecySmart, as it is more suitable to use secondary cells but without energy harvesting units.

TABLE OF CONTENTS

ABBREVIATIONS

AI: Artificial intelligence

CAPEX: Capital expenditure

CBC: Cable-based capacitor

CO_2: Carbon dioxide

DSSC: Dye-sensitized solar cell

EH: Energy harvester

EV: Electric vehicle

FC: Fuel cell

H_2: Hydrogen

ICT: Information and communications technology

ID: Identification

IoT: Internet of Things

LCA: Life cycle analysis

Li-ion: Lithium ion

LiPO: Lithium ion polymer

MSc: Master of Science

NiCd: Nickel cadmium

NiMH: Nickel-metal hydride

NO_x: Nitrogen oxides

OPEX: Operational expenditure

PC: Personal computer

PCB: Printed circuit board

PV: Photovoltaic

RFID: Radio frequency identification

R&D: Research and development

SO_x: Sulfur oxides

1 INTRODUCTION

1.1 Internet of Things

The simplest definition of IoT is the interlinking of everyday objects using internet connectivity. The major technologies that support IoT are data analytics and cloud computing. The Internet of Things (IoT) is a system of interrelated computing devices, mechanical and digital machines, objects, animals or people identified uniquely with an ability to transfer data over a network without requiring explicit human intervention (Gillis, 2021).

An IoT system or platform includes the following elements:

1) IoT application: establishing system boundaries and expected outcome/performance parameters.

2) IoT devices: sensors and actuators in the framework.

3) IoT gateway: communication channel with certain regulations for smooth flow of acquired data. An IoT gateway device ensures routing the data into the IoT system and establishing bi-directional communications between the device-to-gateway and gateway-to-cloud (Motlagh *et al.*, 2020). Further the communication protocols enable effective transmission of data with controllers for decision making.

4) Data storage: efficient storage of massive amounts of data acquired from multiple sources.

5) Data analytics: working upon the stored data and analysis offline or real-time with the help of cloud or edge servers completed the IoT platform.

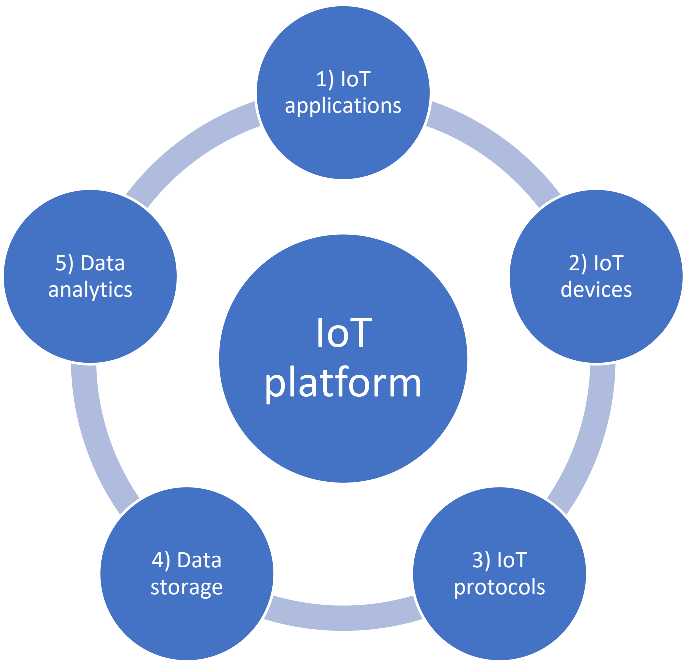


Figure 1. Basic entities in an IoT platform (Motlagh *et al.*, 2020)

Currently, IoT is having many applications in multiple sectors: energy sector, waste management, industrial processes, weather forecast, etc.

Despite the striking advantages of IoT in the multiple sectors, a few challenges that need to be addressed can be faced, especially at the initial stage when these technologies have not reached enough levels of maturity.

For the energy sector, the challenges of existing IoT-based solutions are mainly related to energy consumption, the integration of IoT with other subsystems, user's privacy, security, meeting IoT standards and the architecture design (Motlagh *et al.*, 2020). For the waste management sector, the same challenges exist and need to be solved for wider adoption. These issues and their respective solutions and benefits are summarized in Table 1.

Table 1. Challenges, solutions and benefits of IoT (Motlagh et al., 2020)

Challenge	Issue	Solution	Benefit
Architecture design	Providing a reliable end-to-end connection; diverse technologies	Using heterogeneous reference architectures; applying open standard	Interconnecting things and people; scalability
Integration of IoT with subsystems	Data management; merging with existing systems	Designing co-simulation models; modelling integrated energy systems	Real-time data among devices and subsystems; reduction in cost of maintenance
Standardization	Massive deployment of IoT devices; inconsistency	Defining a system of systems; open information models and protocols	Consistency among various IoT devices; covering various technologies
Energy Consumption	Transmission of high data rate; efficient energy consumption	Designing efficient communication protocols; distributed computing techniques	Energy savings
IoT security	Threats and cyber-attacks	Encryption schemes, distributed control systems	Improved security
User privacy	Maintaining users' personal information	Asking for users' permission	Enables better decision-making

However, the challenge to be addressed in this work is about energy generation and storage for wireless IoT devices to avoid the current dependence on batteries.

1.2 Problem under study

The amount of IoT devices is growing at a fast rate. By 2021, there is an expected growth of 9% in the amount of total IoT connected devices, raising up to 12.3 billion globally (Sinha, 2021). In 2020, the total IoT market worldwide was worth 389 million U.S. dollars with a forecasted increase to one trillion in 2030, doubling the revenues and tipling the amount of devices in the decade. Within these figures, they are included all types of connected devices, such as consumer devices like smartphones or wearables, industrial sensors, connected vehicles, payment terminals and more, being consumer electronics the major share with 35% and an expected increase to 45% (Holst, 2021).

In consumer IoT devices, the most common power supply is to have wired connections and rechargeable batteries, which is still not a major problem. However, for industrial IoT, the devices are usually placed in unfavorable conditions and many times without easy access, so the maintenance costs become increased with more sensors being deployed each time (ONiO, 2020). Weather sensors can be placed at different spots in the city or in remote natural areas like the top of a mountain. While it is vital to sustain the operation of the sensors, it is also important to avoid replacement of batteries. Most times it is more expensive the operation to change a battery than the cost of the battery itself. Moreover, IoT sensors are mostly used for improving the efficiency of operations to avoid costs and reducing the environmental impact of any process. In contradiction, with batteries in sensors, additional logistics and efforts are being added into the system (de Wolff, 2021).

The main issues when using batteries are the following:

1. They have limited lifespans: at some point there will be a need of replacing a battery. This issue will be addressed later on this work.
2. Mineral scarcity: specially lithium, which is highly used for batteries (both primary and secondary cells) is a mineral which is considered a rare material, while the demand for it is increasing with the battery industry growing. Also, the mining of lithium is a very harmful process for the environment, causing water shortage and air pollution. A clear example is what occurred in the Atacama region of Chile, where the mining of lithium consumed out 65% of the region's water (Murray, 2019).
3. Maintenance costs: for some sensors, the cost of replacing batteries can become even more expensive than the sensor and battery together.
4. Environmental impact: batteries, when disposed, are considered in most countries as a hazardous waste and require a specific treatment different from landfilling or incineration. This is due to their toxicity, inflammability, and reactivity levels (Valoriza Medioambiente, 2021).

According to de Wolff, if there are one trillion IoT devices worldwide and battery lifespan achieve to get 10 year duration in average, which is the industry goal, there would be more than 270 million battery changes every day (de Wolff, 2021).

In spite of the before described issues with batteries, there are already some success cases where it was possible to deploy batery-less sensors. For example, Valoriza is operating sensors with recovered heat in machinery thanks to AEInnova's heat energy harvesters (Valoriza Medioambiente, 2021), and the company Everactive deployed 1,200 steam-powered sensors in one industrial facility, helping their client to save 2,5 million U.S. dollars and aproximately 34,000 tons of CO_2 (de Wolff, 2021).

Nevertheless, most of the advances have been done in sensors for industrial facilities, where there is a controlled environment with more constant and predictable conditions. In the contrary, remote or stand-alone outdoors devices still have not found a wide adoptable solution. For example, in the waste management sector most IoT devices are working with primary cells. This applies for waste characterization devices, filling level sensors, access control with lockable lids, ID recognition with RFID technologhy, and more.

1.3 Objectives

The objectives for the particular case study to be explained in next sections is to find the best power supply alternatives that can:

1. Reduce the environmental impact of the devices.

2. Maintain or improve the current technical performances (power and energy).
3. Increase less than 25% the CAPEX and OPEX[1] from the final client's point of view or even maintain or reduce the current ones.
4. Be available on less than 45 days for those solutions that do not need any development, or have a development period of less than 6 months for more complex and customized alternatives.

The general outcomes of the thesis should be:

1. A framework to find the best sustainable power supply solution for stand-alone IoT devices that could serve as a guide for other ICT companies with IoT devices.
2. A state-of-the-art preview of different technologies to power IoT devices.

The outcomes that are particular for the case study should be:

3. A set of power supply alternatives (generation and storage) for replacing the existing power supply or offering a more sustainable option.
4. An analysis report (MSc Thesis final deliverable) of how selected alternatives will modify the technical performance (can be better or equal), the environmental impact (should be less harmful), and the economic performance (can be cheaper or more expensive), for decision makers in the case study's company.
5. A preliminary decision on which alternatives to move forward with and how to proceed with the next steps for the integration or, in case any development is needed, how to proceed with it.

The focus will be on the case study devices that wil be explained in the following section, but it is also intended that the analysis performed would be useful for different IoT devices.

Finally, the storage solutions analysis can also serve for devices with batteries like electric scooters, smartphones, PCs, etc.

[1] For CAPEX, it will be considered: the purchasing cost of energy harvester and/or storage units that have the same or longer lifespan than the device they operate, and all the cost of actions needed for the technology to be able to work for the purposes they were created (installation, initial set-up, etc.). For OPEX, it will be considered: the purchase of storage elements (like batteries) that have less lifespan than the device they supply, and all the cost of the actions needed for the technology to keep working for the purposes they were created (refilling, recharging, replacement, calibrating, revising, transportations, etc.).

2 METHOD

2.1 Research method

2.1.1 Preliminary alternatives review

The first step will be to have a general overview of all existing or potential solutions for the topic. Therefore, a lists of candidates will be obtained. This early preview will be done by means of scientic papers and articles related to the topic of IoT devices with the need to guarantee self-autonomy and the ways to achieve it, specifically from a power supply point of view. An example of one source is Häggström, F. and Delsing, J. (2018) "IoT Energy Storage - A Forecast". This type of literature usually facilitates comparisons among different technologies, so it is a good starting point from which to understand main advantages and disadvantages for each.

As it is a fast moving sector, the aim is to study literature from 2010 onwards prioritizing publications from 2018 onwards, then from 2015 to 2018, and with less importance from 2010 to 2015. Moreover, particularly when reviewing scientific papers, it can be found that those later papers from 2018 onwards usually build upon findings of previous ones.

After having a big picture of almost all the technologies being currently used or researched in the field, the next step is to deep-dive into each of them. The preliminary review of each energy harvesting and storage technology will be done by means of research that will include:

1. Literature review: it includes scientific papers and articles by experts. This will be used specially for technologies that are not yet mature for use in commercial applications, at least for IoT devices.
2. Market research: it implies looking for existing solutions in the market for IoT devices or other applications that could have assimilable energy consumptions.

Therefore, for each technology, one or both methodologies will be carried out to understand the level of maturity of the technology, the availability of supply in the market, and a first technical understanding of how the technology works and its applications.

For example, for conventional solar photovoltaics, it is easily found that there are multiple IoT applications that use this technology as energy harvester and multiple suppliers can be found in the market (browsed via the internet), therefore there is no need to make a literature review. Technologies like this would be considered mature. The same happens with primary and secondary cells.

On the other hand, piezoelectric energy harvesters appear as a promising solution which is not yet widely found in the market. In this case, literature review on scientific papers will be a better source of understanding of the advantages, applications, specifications and other aspects of the technology. Hence, the literature review is first performed and then it is researched if there is any existing company developing the solution for similar applications.

When studying scientific papers for one particular technology, usually there is a case study in them to find relevant results. Then, papers in which the case study was similar to the applications studied in this work were prefered. For example, a study of hydrogen fuel cells and electrolyzers in low power electronics like portable devices will be more convenient than the of the same technology applied to electric vehicles or large buildings.

Finally, when this methodology is performed for all candidates, it will be possible to have an understanding of the advantages and disadvantages of each technology, the applications it currently has, and the level of maturity. The level of maturity was classified into the following three categories:

- Research: technology still not available in the market for any application, only lab prototypes.
- Early stage: technology has some products in the market but still not widely deployed, and less for the studied applications.
- Commercial: the technology is widely offered in the market.

2.1.2 Pre-selection of alternatives

From the preliminary alternatives review to the conclusions, the study will be done with focus on a case study. The same will be explained in the next section. The case study is used to have a real case to be tight to, because it would mistaken to say that there is one best alternative for all IoT devices.

Therefore, the pre-selection of alternatives will be done on a qualititative basis, based on the previous research and thinking on solutions that solve the general problem for the particular devices of the case study. Basically, technologies that do not have fit for the applications of the case study due to technical issues or because the level of maturity is not enough to be incorporated in the short or medium term into an IoT device will be discarded. The most preferred technologies in terms of maturity will be those in commercial or early stages.

2.1.3 Technical assessment

The evaluation of the technical feasibility for each technology will be done totally upon existing market solutions for the application in the devices of the case study, or that could be aplicable to them. For this, suppliers for each technology will be searched and their products evaluated. When needed, interviews with representant of the supplying companies will be carried out. In the conversations with the suppliers, the applications will be explained and the idea is to get feedback on whether the technology gathers or not the relevan technical parameters to be a suitable fit. Also, the intention is that it is the supplier who provides a first insight of which particular model or unit of their portfolio should be used, in which quantity, and other considerations. For this, it will be needed to provide them information about the current consumption of devices and the current power supply, always by previously signing a non-disclosure agreement. Besides, for those companies that already include enough technical data in their webpage through descriptions or datasheets, a meeting might not be needed.

After gathering all the relevant information from the suppliers, in most cases own calculations might be needed. These should not be in much detail as the idea of this work is to have a pre-definition to move forward with a further and more exhaustive development. For the calculations, the only software tool used will be Excel.

2.1.4 Environmental assessment

Due to the lack of detailed information regarding the environmental impact of the products, the environmental assessment will be carried out mainly by means of collecting results from different scientific papers and life-cycle analysis. Different sources reviewing the various types of one same technology will be reviewed.

The ideal situation would be that in which:

1) First, it is possible to find enough literature to compare different variations within a technology. For example, LCAs comparing silicon based PV modules with dye-sensitized ones are a good way of understanding which of the two types of PV is more environmnetal friendly. Another example would be comparison for same applications of different secondary cells chemistries. Fortunately, regarding this first point it was possible to find literature for all technologies studied.
2) Second, it is possible to find enough literature to compare different technologies for energy harvesting and storage. An example could be a scientific publication comparing the use and environmental impact of solar photovoltaics and fuel cells for a low power electronics application. However, for this type of comparison it is not so easy to find enough material as desired (at least in the timeframe of dedication of this Master thesis).

With this approach, it will be possible to have a good understanding of how each variant within each technology will affect the environmental impact from other case studies (those of the scientific publications), with a not so clear picture of how each technology could help perform the environmental aspect in comparison to others.

To have a more precise environmental assessment for the particular applications studied in this work, the recommended way would be to perform a LCA for each scenario with the different technologies combinations applied to the studied devices. However, this requires a workload that in itself could be the topic of another Master thesis. Also, from a point of view of a company, it might not be possible or desired to alocate so much resources to such a task, even when the goal is to improve the environmental impact of the products offered. In the future, if legislations make it mandatory to include environmental footprint information in all products, this task could be much easier because when already evaluating alternatives, these would have information about their impact. Currently, data regarding technical performance and costs is available for all technologies, but not about environmental impact. Of course, that companies offering an eco-friendly technology make marketing with it, but usually with a qualitative information rather than detailed and quantified data.

2.1.5 Economic assessment

The economical evaluation will be done according to market values of the studied technologies. The study will be done based on particular products on each technology.

For those technologies analyzed in the technical assessment in which an interview was held with the supplier, then it will be requested to them to provide quotations for different scales. Then, for some technologies the costs can be directly obtained from the suppliers' websites. Finally, different marketplaces will be used to find the costs of comparable products in order to ensure that there is more than one reference price for each technology.

Upon this, own calculations will be done, specifically to calculate the associated OPEX and part of the CAPEX of different combinations of technologies (energy harvester and storage devices). Along with the purchase of the technologies themselves, there will be smaller development cost (like redesigns in the electronic board), installation and maintenance costs that will differ from one technology to the other. As in the technical assessment, all calculations are kept simple to have a broad picture and not a precise budget with all the details for all technologies.

2.1.6 Selection of best alternative

For each of the devices of the case study, the selection of best alternative will be decided upon a qualitative analysis based on the previously assessed criteria. If within one of the assessments, there is one aspect that makes a technology not to be suitable for the studied applications, in contrast with the defined objectives, then these technology will be discarded. Therefore, after the pre-selection of alternatives is done, the different assessments aim to evaluate and compare the technologies and discard those that are not suitable. After the three assessment are done, the final selection will be done between the technologies that arrived to the final decision. In case there is more than one option, a decision will be taken according to the analysis on the three aspects and selecting the combination that best suits to the objectives proposed.

To summarize this section, Figure 2 is presented to schematize the methodology used for each stage as described before.

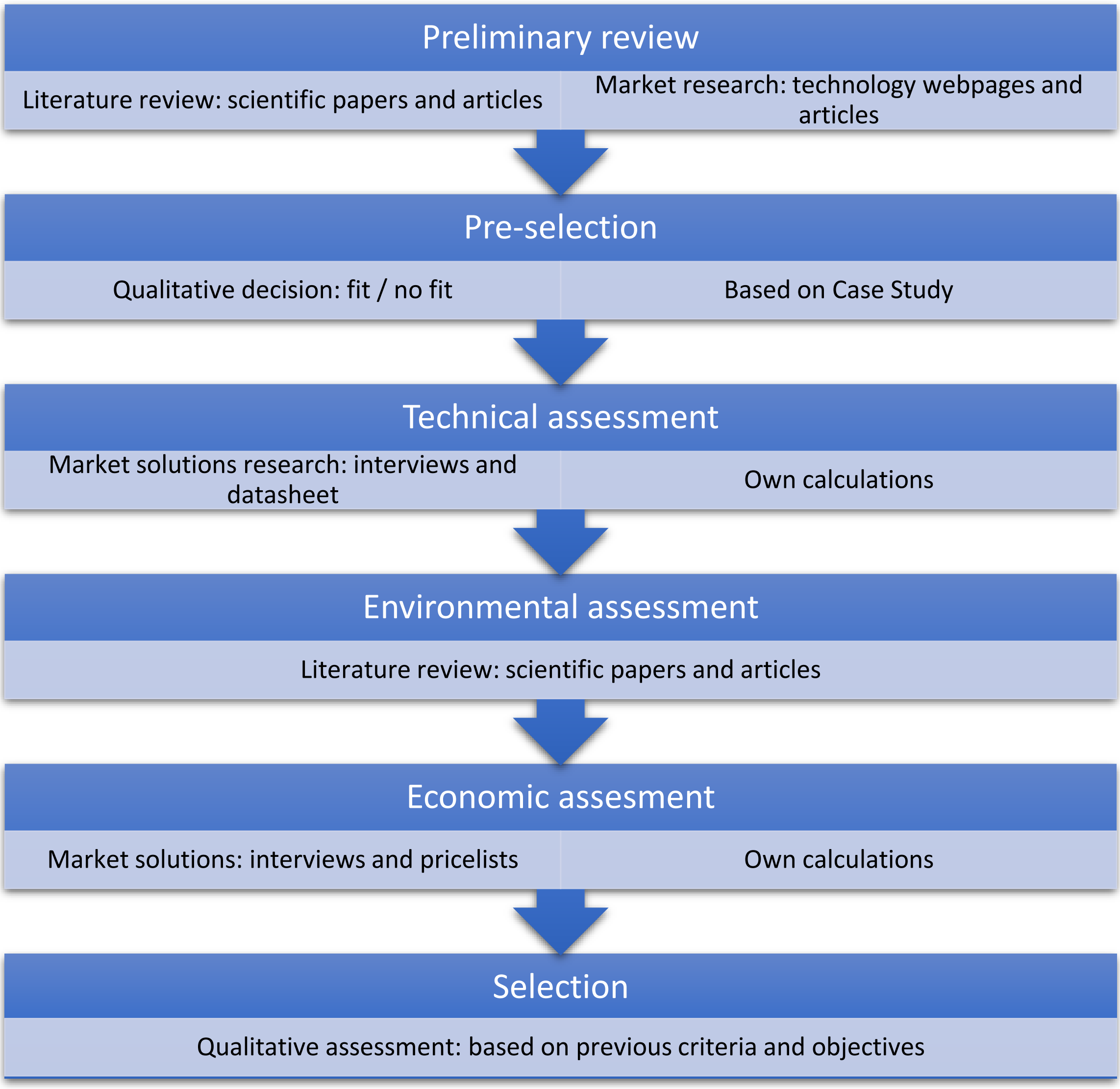


Figure 2. Scheme of methodology used for each stage.

As an example, Figure 3 shows a scheme of how along the stages of this work, the different technologies were discarded. The reasons behind the elimination of each technology will be described along this work. The scheme is for RecySmart device, one of the case study devices to be explained in the next section.

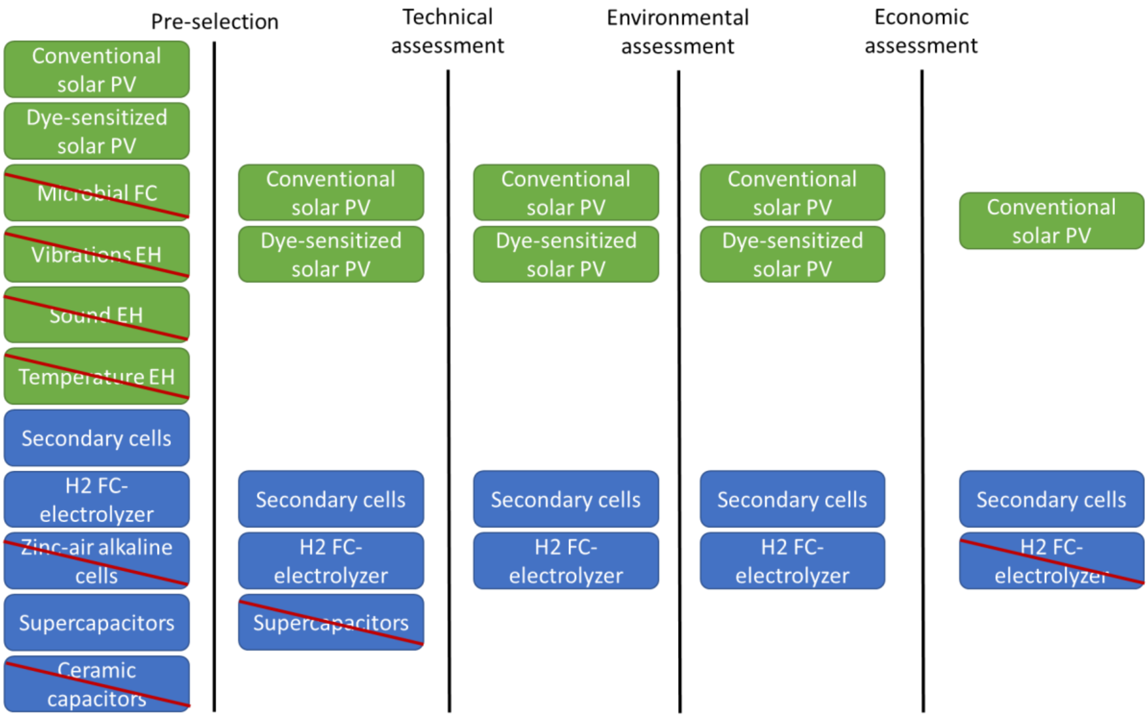


Figure 3. Scheme of decision flow for different technologies for energy harvesting (green) and storage (blue) along the stages of this work for RecySmart device

2.2 Case study

2.2.1 Recircula Solutions

Recircula Solutions (https://recirculasolutions.com/) provides technology for Circular Economy. Based in Barcelona, it strives for improving Sustainability and Smart Cities. It leads innovation in Waste Management sector by designing and distributing European patented hardware and software tools for Rewarding, Deposit Refund and Reusable Packaging schemes.

Founded in 2017, with operations starting in 2019, Recircula Solutions is about to receive two European patents (for RecySmart) and is sending demos of RecySmart to many European countries. Besides, it distributes technology for the Waste Management sector from other European suppliers. Currently, it is partner of Sensoneo which provides hardware and software for Asset Management, Waste Monitoring and Route Planning all for waste managers.

Recircula Solutions is supported by EIT InnoEnergy (principal investor) and has received several recognitions thanks to our continuous search to overcome current challenges.

The author of this work joined Recircula Solutions in February 2020 with the role of Business Development Manager.

2.2.2 RecySmart

2.2.2.1 RecySmart technology

RecySmart technology was created to solve the problem of low recycling rates in Europe. With *RecySmart*, city councils and waste managers will be able to engage citizens in an active role thanks to rewarding.

With *RecySmart*, the obtained results are:

a. Increase of recovery rates for the glass and light packaging fractions between 20-30%.

b. Decrease in the amount of impropers in the light packaging fraction between 5-20%.

c. The fuel used will decrease in 15% thanks to the route optimization which becomes possible with the filling volume status of the containers.

d. Boost local commerce and economy of the city.

e. Fight against food waste with the incentives program: 1/3 of all food is wasted and should be avoided.

2.2.2.2 How it works?

Recycling process

1) The citizen logs in with the smartphone (via *RecySmart citizen app*) or RFID card in the *RecySmart device*.
2) Connection with the server is established and the citizen can start.
3) The citizen throws the items one by one. The citizen will receive recycling points for the packaging that is correctly recycled.
4) The information of this recycling process is sent to the servers.
5) The *RecySmart* device will also send to the platform the filling volume so the manager can know when to collect the waste in that container.

Incentive program

1) The citizen exchanges recycling points for rewards in *RecySmart citizen app*.
2) After a reward is selected, the citizen receives within the app a unique code (can be QR or other form) that contains the discount selected.
3) In case of a physical shop, the QR code is scanned by the shop employee and the discount is successfully granted to the citizen. In case of an app (for example for shared mobility), the code is applied by the citizen to receive the discount within the app.
4) The citizen enjoys the discount, the business enjoys their client. The environment wins. We all win.

More details about RecySmart can be found in References (Recircula Solutions, 2021).

2.2.2.3 RecySmart device

RecySmart device is the fundamental key of the project as it has the function of recognizing packaging, counting items, identifying and interacting with citizens and sending everything to the *WM Platform* generating a database. The *RecySmart* device is designed with the aim of being adaptable to every type of containers avoiding any modifications (in any case an external mechanical part can be applied for facilitating the adaptation) and also is resistant to any adverse conditions, which makes *RecySmart* a totally scalable solution. Moreover, it has the possibility to include an ultrasonic sensor for measuring the filling level.

RecySmart RDS is implemented for the light packaging and glass fractions. The packaging items recycled by citizens of both fractions (all glass, plastic bottles, metal cans and Tetra Briks) are identified in real-time with the artificial intelligence system. The citizens need to previously log in by the *RecySmart Citizen app* (or another integrated app) or with RFID card to have the recycling data associated with the user. The device can also be equipped with an ultrasonic sensor for measuring the filling level, and can also be equipped with a code scanner to read packaging codes (barcode, QR, etc.).

2.2.2.4 Current situation

Currently, RecySmart uses non-rechargeable lithium batteries, as many other IoT technologies. Specifically, the battery type is Lithium-thionyl chloride – Li-$SOCl_2$. Technicians at Recircula Solution declare that the batteries should last between 12-16 months under normal conditions and once the product reaches certain level of maturity (currently they say it should last between 6-9 months). In Table 2, the electric specifications of RecySmart RDS are shown. These are type ER34615, 3.6 V and size D with 19 Ah capacity. In total, the energy of the 3 batteries is then 205.2 Wh.

Table 2. RecySmart RDS electric specifications (Recircula Solutions, 2021)

Parameter	Symbol	Value	Units
Absolute Maximum Voltage	Vmax	5.5	V
Absolute Maximum Current	Imax	350	mA
Recommended Supply Voltage	Vcc	2.5 to 5	V
Supply Current (Active)	$Iq_{(Active)}$	150	mA
Supply Current (Sleep)	$Iq_{(sleep)}$	[TBD] (< 5 by design)	mA
Required space for integration	WxLxH	80x150x15	mm

2.2.3 Single Sensor

As a secondary device to take into consideration for the analysis to be applicable for more devices than RecySmart, the Single Sensor by Sensoneo, Recircula Solutions' partner, will be considered. The Single Sensor consists of an ultrasonic sensor to measure the filling level of containers that can connect via Bluetooth, LoRaWAN and NB-IoT or Sigfox. The battery type of Single Sensor is also Lithium-thionyl chloride – Li-$SOCl_2$. It carries 2 batteries LS14500 with voltage of 3.6 V and capacity of 2,600 mAh. Under normal conditions, the batteries should last up to 7 years (depending on local temperature, type and position of the bin, master/slave role and frequency of measurement).

3 ALTERNATIVES REVIEW

In the following section, a set of alternatives for energy generation and storage will be covered according to the current state-of-the-art of different technologies to understand which of them could be suitable to power RecySmart and other IoT devices better than batteries.

3.1 Energy generation

3.1.1 Solar photovoltaic

3.1.1.1 Conventional solar modules

Solar cells are one of the main energy harvesters used for IoT devices when a clean source of energy is desired. In waste management sector, the most seen use for solar cells in IoT devices for the waste management sector is in the so-called solar compactor bins. These are smart bins that consist of a street bin equipped with a compaction unit to reduce waste volume and also carry a battery and the solar cell to recharge it. Also, it is common that the solar compactor bins communicate the filling level. Currently, Recircula is developing together with Binology (Russian start-up) their own solar compactor bin with a RecySmart device included.

For a solar compactor bin, it is easier to integrate the solar cell into the bin because all the product is assembled together before placing it in public spaces. However, when it comes to IoT devices that need to be installed in the already existing infrastructure, it is not so straightforward to integrate a solar cell, mainly because in most cases the device will not be installed in a position where the solar cell will perform good.

Recircula Solutions' team tried solar cells for powering previous versions of RecySmart in the past and the trials did not work out well. The main problem was that the system was not working properly, meaning that the solar cell did not recharge the battery. Besides, recently our battery supplier commented that all the clients they have that had tried solar cells and rechargeable batteries to power IoT devices, have had bad experiences and ended up using only non-rechargeable batteries.

Another inconvenient with solar cells was that RecySmart is installed at the mouth of the waste bin in a vertical position, therefore the solar cell would work better if positioned at the top of the bin, and this is a problem because it creates the need for external cables in a waste bin that is constantly exposed to shaking and which makes installation more complicated. Taking as another example the Single Sensor, this device must be mounted in the inside part of the bin at the top, and considering that the solar cell should be installed in the outside, there is the same problem of external cables and complicated installation.

Nevertheless, considering the current state of technological advance of solar cells, wide adoption and acceptance from the public, and cost reduction from one side, and that the team was not expert enough back in 2019, solar cells will be analyzed in detail as a possible option for energy generation as it is currently the most used energy generation for IoT devices as an alternative for non-rechargeable batteries.

3.1.1.2 Dye-sensitized solar cells

As a good alternative to normal solar cells, dye-sensitized solar cells (DSSCs) have been developed to be able to generate power over a wide range of lighting and temperature conditions. Fujikura's DSSCs (Fujikura, 2020) have been specially designed for IoT devices, making the integration simpler. The key features that give them advantages compared to normal solar cells are the following:

1. High power generation over a wide range of lighting conditions: capable of generating electricity anywhere: in sunlight, in shade, in bad weather, indoors, etc.
2. High power generation over a wide range of temperatures: capable of supplying electricity from -30º C to +60ºC (the upper range is very important in Spain as in summer high temperatures are considerable).
3. Can be installed without regard to the position of the light source: since power can be generated from scattered light, there is no need to make sure the cells are oriented towards the light source. This is a very important aspect because it allows the solar cell to be integrated directly into RecySmart device, making the installation and maintenance simpler and less costly, while also improving the anti-vandalism feature desired for any IoT device as it would not be possible to take off the solar cell.
4. The DSSC can be partially under shadow: these cells avoid the problem that most multiple series solar cells can experience due to shadows (so called hot spot).
5. Durable enough to be used both indoors and outdoors: Fujikura's DSSCs were specially designed for long-term power supply solving issues for which other DSSCs were criticized.

3.1.2 Piezoelectric energy harvester

3.1.2.1 Vibrations energy harvester

For micro-scale energy generation, it is possible to use devices that utilize waste energy from the environment in the form of vibrations and transform it into practical energy. Among the mechanisms of harvesting mechanical vibrations, the piezoelectric is the most preferred due to the simpler geometries of EH, higher power densities, easier integration with microscale electronic devices and because it does not require an external input voltage (Asthana and Khanna, 2019). Other mechanisms are electrostatic and electromagnetic.

The inputs to the system provided by ambient vibrations are frequency and acceleration which lead to a mechanical force. Within the structural design, the cantilever is the most used as it produces more stress on its surface when compared to others (under same force). Asthana and Khanna propose a model using a new cantilever structure based on conventional see-saw swing (long board which is balance on a fixed part in the middle, usually with two weights, one at each end).

An energy harvester of this type occupies less than 1 cm3 which makes it very convenient for incorporating to IoT devices. The see-saw harvester can generate 0.175 mW at 1g acceleration which could be improved with circuitry.

The Spanish company Energiot developed a patented piezoelectric technology to harvest residual ambient energy. The device counts with innovative aspects like the use of nanowires of ZnO as transductor and the use of microelectronics like those used in microchips, providing cost advantages and ease of integration. The technologies are being applied to Smart Grids where the electromagnetic field of transmission lines is used to generate electricity. Another application is to take advantage of the energy from the vibrations of a train's wheel to feed a sensor to monitor the status of the bearings (Energiot, 2021).

In a first contact with Energiot, they said that a piezoelectric generator would not be suitable for the application of RecySmart because there are not constant vibrations. Moreover, checking with other suppliers and labs, it was confirmed that current commercial applications work only under environments with fixed frequency, as the bandwidth of kinetic energy harvesting generators is often a few Hz (Pedersen, 2021). This is the reason why most applications are used in motors and rotating bodies (like train wheels).

However, there are possibilities to adjust generation to variable motion ensuring high efficiency. One option is through mechanical means, using the system's inertia to change the resonance frequency, with the disadvantage of increased size and complexity of the device. The second option is by changing the load electronically, with the disadvantage of increased energy consumption in the power control circuit. A combination of both approaches exists and results in the form of a variable magnetic field around the generator.

3.1.2.2 Sound energy harvester

The same as with vibration energy harvesters, it is also possible to harvest sound energy. In the end, sound is a form of air vibration. Sound energy is available in abundance (specially in urban areas). However, it has low energy density in comparison to other alternatives (Choi, Jung and Kang, 2018).

For sound energy, the ambient sound waves are collected and amplified by a resonator or by an acoustic metamaterial. Later, these amplified sound waves are converted into electrical energy by a conversion method like those to capture vibration energy: piezoelectric, electromagnetic, or triboelectric. The most typical combination for a sound energy harvester is a resonator, a membrane and piezoelectric material. In Figure 4 the different combinations for sound energy harvesters are shown.

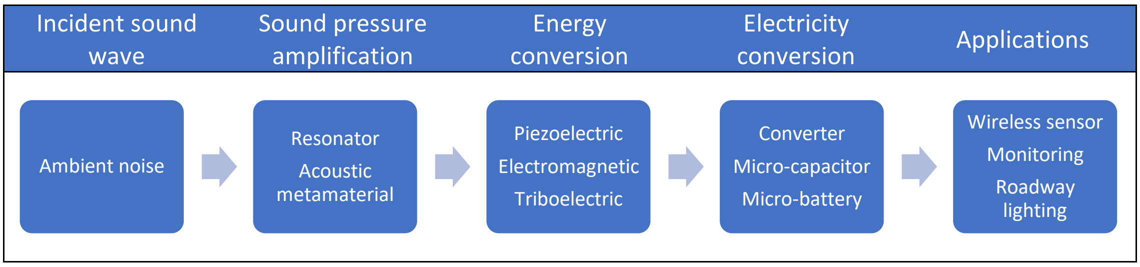


Figure 4. Schematic of sound energy harvesting (Choi, Jung and Kang, 2018)

Nevertheless, acoustic metamaterials are becoming very studied because they allow to decrease the size of sound energy harvesters considerably. This is basically because the amplification they generate depends on the geometrical shape and the material used, rather than on the size of the amplifier. This is why combination of both types of amplifiers are tried.

In conclusion, the resonators are better amplifying the sound wave but increase the size of the device, while acoustic metamaterials do not depend on their dimensions so are more applicable for small low power devices. This technology is still in early stage and could not be used for the current IoT applications. One of the challenges to be solved is the same as in vibration energy harvester, which is the adaptation to variable pressure levels and frequencies. Also, as Choi, Jung and Kang remarked, all the prototypes tried with different combinations of amplifier and energy converters work over a sound pressure level of 100 dB, being this approximately 100% higher than the SPL of a normal conversation. One of the most promising application to be studied is in highways.

3.1.3 Temperature energy harvester

Another form of ambient energy is temperature. The main way to harvest is by means of the thermoelectric technology. There are commercial thermoelectric generators that deliver output power in the range from µW to kW. The thermoelectric effect is based on temperature gradients that generate a heat flow through the generator and a part of it is converted to electrical energy. Power output and efficiency vary significantly with materials properties.

Pyroelectric materials are an alternative to converting heat energy into electricity. These do not need a temperature gradient (spatial), but temporal temperature changes. According to the simulations performed by Seabald, Guyomar and Agbossou, the output power when using a linear pyroelectric material can be 10 times greater than that of a thermoelectric one, and performance can be increased by 10 to 100 when using nonlinear pyroelectric materials (Sebald, Guyomar and Agbossou, 2009). While thermoelectric materials can only reach a maximum efficiency of 1.7% of Carnot efficiency, with pyroelectric device using layers of different materials it can be expected a maximum of 50% of Carnot efficiency.

Nevertheless, the main drawback for pyroelectric technology relies in the need for temperature time variations (daily variations seems not be quick enough), which are less common in nature than temperature space gradients. Some applications may transform spatial gradients to time varying temperatures by means of a cyclic pumping unit. The pump power consumption could be as little as 2% of the harvested energy, but still it adds more complexity to the system.

In conclusion, the efficiency for these technologies is still lower than other alternatives and seem no to be widely studied, meaning that they are not ready for market application. Also, considering that one of the IoT devices studied here is more demanding than a normal IoT sensor, and there are not applications even for normal sensors of these energy harvester, then temperature energy harvesting will not be considered for further analysis.

3.2 Energy storage

3.2.1 Primary cells

IoT devices depending totally on non-rechargeable cells have a limited lifetime which depends on the total energy provided. Material and volume are key parameters on determining the duration of the batteries, as also ambient conditions affect considerably their performance. The most common primary cells for portable, wearable and IoT devices are Lithium based.

However, primary cells are still the most used energy storage technology and this is mainly for the following reasons (Häggström and Delsing, 2018):

- They have high storage capacities.
- They are widely known and deployed with sufficient market supply.
- There are multiple primary cells that adapt to various different needs.
- The costs are incredibly low in comparison to other alternatives.
- The incorporation of them into any device is very simple and no other parts are required.
- They provide stable energy when needed.

3.2.2 Secondary cells

Rechargeable batteries have the main advantage against primary cells that they can be recharged, therefore its lifetime is extended and maintenance reduced. Nevertheless, the recharging has its limits as they suffer from cyclic degradation. Alike primary cells, they have reduced capabilities when working under lower or higher temperatures.

3.2.3 Hydrogen fuel cell - electrolyzer

Fuel cells and hydrogen are arising as the most promising technology to drive us to the next level of energy systems. Currently, hydrogen is being studied for multiple applications because of various advantages, being the most important that it is a very clean technology both for energy generation (fuel cells) and storage (hydrogen), with very high energy density. Among other advantages, one that is key for IoT devices, wearables and small items is that fuel cells can be scaled up or down in size without compromising the performance, therefore it is possible to have very small fuel cells powering IoT devices. For example, in 2016, the British company Intelligent Energy successfully tried powering an iPhone 6 with a fuel cell. The cells can be done very thin and can fit the interior of the smartphones without need of modifying the device in shape or size (Worthman, 2020).

Akimoto et al. carried out an experiment to compare the performance of a fuel cell and a lithium-ion battery, both powering an IoT device with a Raspberry Pi[2] (Akimoto *et al.*, 2020). After their analysis, they concluded that fuel cells could be a suitable (even better) alternative for IoT devices but that the price is an important barrier.

Moreover, some other challenges relate to its volatility, storage and availability. First, hydrogen is extremely volatile, so it must be contained in a strictly controlled environment, which might not be possible in small devices. Second, due to the low density, hydrogen containers must be very watertight. Finally, fuel cells consume hydrogen and leave water and heat as products. This represents three issues:

1. hydrogen should be supplied again, or the electrolysis of water is necessary to reverse the reaction (for example with a solar PV module);
2. in case hydrogen is supplied externally, then water must be removed;
3. in most applications heat will not be desired and must be removed, involving a cooling system (air or water pumped) or relying on natural ventilation that, although simpler, is not as effective and might result in lower performance or device damaging.

Despite these drawbacks, there is a worldwide interest in this particular technology, and advances are being done in multiple applications. It is worth mentioning the case of the Swedish company myFC that developed LAMINA™, fuel cells that are flexible in shape and form (myFC, 2021). They use hydrogen gas and a Proton Exchange Membrane fuel cell to generate power. They are designed to use passive air feed and do not carry bi-polar plate, making them less costly and easier to manufacture.

The company provides customized solutions from a single fuel cell, fuel cells modules, to fuel cell systems. The last one comprehends a hybrid system between battery and fuel cell to combine the advantages of both systems that provides reliability, improved electric performance and lifetime optimization.

The applications in which they are more focused are those of EVs, other forms of portable mobility (like scooters or e-bikes) and mobile devices. In all of these applications, there is a connection to electricity network at some point, so the reaction can be reversed (electrolysis of

[2] The Raspberry Pi is a small sized computer that can be plugged to conventional monitors and uses standard keyboard an mouse

water) to generate the H_2 gas. Therefore, it is still needed to validate how the best use for them would be in stand-alone devices.

The Korean company XFC also seems to have developed fuel cell solutions targeting portable devices like smart glasses or smartphones back in 2012 (XFC, 2019).

3.2.4 Supercapacitors

Supercapacitors have lower energy density than batteries but they do not experience cyclic degradation as rechargeable batteries do. However, it is much common to have energy losses within a supercapacitor due to current leakages and internal energy distribution, so they are not very suitable for long-term storage. Also, this is a total constrain in the cases that the leakage represents as much as the power output of the energy harvester. Although these storage devices cannot work over 85ºC, this limit is not a stopper for IoT devices placed under ambient conditions.

The company Capacitech has developed a flexible cable-based supercapacitor designed to be integrated off PCB and to provide peak power assistance (Passive Components, 2021). These supercapacitors are intended to overcome up to some extent the challenges of intermittency and low power of energy harvesters, by accumulating the energy and liberating it faster, making it possible to carry out the most demanding tasks of IoT devices which are usually related to data sending.

3.2.5 Ceramic capacitors

Although electrolytic capacitors do suffer from degradation, its causes do not appear for most IoT appliances therefore it is not an issue. Moreover, ceramic capacitors have very little degradation and the capacitance becomes stable after certain period (10^4 hours) (Häggström and Delsing, 2018). Currently, ceramic capacitors have more energy density than electrolytic ones and probably they will become better in this sense than supercapacitors.

Thanks to these advances, ceramic capacitors have satisfactory energy densities, almost no degradation and low current leakage, which make them one of the most promising alternatives for short and medium term storage in combination with energy harvesters. It was expected that by this year (2021), ceramic capacitors would be reaching their theorical maximum energy density of 35 J/cm^2. Nevertheless, with dielectric materials further improvements can be done. This technology seems to be ready for market applications in combination with energy harvesters.

3.3 Comparison

In Table 3 and Table 4, the main advantages and disadvantages for each energy harvesting and storage technologies are listed respectively. Moreover, the applications in which those technologies are currently used and the maturity are described.

Table 3. Qualitative comparison of different energy harvesting technologies

TECHNOLOGY	ADVANTAGES	DISADVANTAGES	APPLICATIONS	STAGE	SOURCE
ENERGY HARVESTING					
Solar PV (conventional)	Widely known technology Visible: good marketing	Climate and time dependent Cabling needed (could be integrated but not good angle)	Utilty scale power plants, distributed generation, IoT	Commercial	-
Dye-sensitized solar cells	Good performance without direct sunlight or cloudy (better than normal PV) and no shading problem Wide range of T (-30 to 60)	Climate and time dependent Less suppliers than normal PV	All types of IoT	Early stage	(Fujikura, 2020)

	Can be integrated in the device and avoid extensive cabling Direct charge to storage, no frequent maintenance needed Visible: good marketing	Needs 2 converters (boost and step-up/down)			
Microbial FC	Carbon-neutral and environmental friendly Similar scheme (Sensor, BLE, app) Can charge supercapacitor or rechargeable battery	Insufficient power (3 hs of generation and charge of supercapacitor represent 30 s of IoT sensor operation) Refill of bacterial substrate Needs MPPT and circuitry to avoid Voltage Reversal and balance disturbances Generation decays as substrate evaporates	Wieless IoT sensor, smartphones, DC motors, radiomodules	Research	(Veerubhotla, Nag and Das, 2019)
Vibrations EH (piezoelectric)	Simple geometry, higher power density, easier integration in microscale, does not require external voltage input Volume < 1 cm3	Not widely deployed	IoT microscale devices: train wheels, electric grid cables	Research	(Asthana and Khanna, 2019)
Sound EH	Resonator Based: More effective to amplify pressure level Acoustic metamaterials based: Reduced size of harvesting devices as it improves according to geometric arrangement of metamaterial rather than size. Hybrid amplification: acoustic metamaterials and resonator amplification makes use of both advantages Hybrid generation: combination of harvesting techniques can increase power output.	Resonator based: Needs resonator for amplification. Acoustic metamaterials based: Complex geometries. Hybrid methods: Complexity of device General: most sound EH work above 100 dB SPL, which relatively higher than normal conversation (40-60 dB)	IoT microscale devices	Research	(Choi, Jung and Kang, 2018)
Temperature EH	Pyroelectric can reach 50% of Carnot efficiency	Efficiency still needs improvement Spatial temperature gradient is easier to get (useful for thermoelectric) but pyroelectric uses time temperature gradient. These can be transformed to one and other but adding more equipment so more space and costs	Wearable devices, industry heat recovery	Research	(Sebald, Guyomar and Agbossou, 2009)

Table 4. Qualitative comparison of different energy storage technologies

TECHNOLOGY	ADVANTAGES	DISADVANTAGES	APPLICATIONS	STAGE	SOURCE
STORAGE					
H_2 FC-Electrolyzer	Higher energy density than Li batteries Rechargeable FC can be done extremely thin	H2 tank needed Cost Heat generation may disturb	IoT devices, wearable devices, smartphones, other applications at medium large scale	Early stage	(XFC, 2019; Akimoto *et al.*, 2020; Worthman, 2020; myFC, 2021)
Primary cells	High energy density Widely developed: validated technology Wide variations for multiple uses	Non-rechargeable Not well suited for long-life (20 years) Environmentaly harmful (hazardous waste)	Multiple	Commercial	(Häggström and Delsing, 2018; Saft Batteries, 2020)
Secondary cells	High energy density Longer life-time than primary cells One cycle has lower performance	Cyclic degradation Not well suited for long-life (20 years) Environmentaly harmful (hazardous waste) High T is limiting	Multiple	Commercial	(Häggström and Delsing, 2018; Saft Batteries, 2020)
Zinc air alkaline cells	Chemical reaction is reversed with air Lifetime 37,5 x conventional lithium primary cell Market-ready but not very known. Contact directly from patent owner. Short-term competitive adv.	Technical team tried and did not experienced the benefits promised by manufacturer	Multiple	Commercial	(Cegasa Energía SLU, 2018)
Supercapacitors	No cyclic degradation Flexible, cable-based, off PCB is possible Fast energy liberation, ideal to provide peak assistance	Lower energy density than batteries High T is limiting (operating < 85ºC) Energy losses considerable due to current leakage	IoT devices with energy harvesters (for ex. solar cell)	Early stage	(Häggström and Delsing, 2018; Passive Components, 2021)
Ceramic capacitors	Satisfactory energy densities Almost no degradation No current leakages	Only for short and medium term storage Storage at smaller scale	PCBs	Commercial	(Häggström and Delsing, 2018)

3.4 Selected alternatives for further analysis

Considering the previous study, the selected alternatives for a deeper analysis and the key reasons will be the following:

1. Conventional solar modules: there are multiple suppliers and options for standard solar cells for IoT devices. They are widely known and accepted, in a mature state of development, with increasing efficiencies and decreasing costs. Besides, as they are visible, they improve the image of the technology and hence making it even more attractive for clients willing to take sustainable actions.
2. Dye-sensitized PV solar cells: this technology will be considered because it does not have the need of facing the cell towards the sky as it performs better with scattered light than standard PV cells. Therefore, this brings the opportunity to embed the DSSC into the device itself, simplifying manufacturing, installation and maintenance considerably.
3. Fuel cells: thanks to the latest developments to reduce fuel cells in size while keeping very high energy density, these can be a suitable alternative to have a sustainable power supply without increasing the size of the device. To use FCs, however, it will be necessary to count with an extra power supply to make the reverse reaction (electrolysis of water). Most probably, FC will be analyzed in combination with Solar PV (standard or DSSC).
4. Secondary cells: they need to be evaluated as a short-medium term storage solution for the solar photovoltaic generation.
5. Supercapacitors: the latest advances in this technology make them considerable for further analysis. They can be suitable for short-term storage of PV generation and providing peak support.

4 RESULTS

4.1 TECHNICAL ASSESSMENT

4.1.1 Demand side management

The first step to analyze whether an energy harvester or storage unit is suitable, is to understand how the demand of the devices behaves. In the end, the IoT device is not more than an electrical load which has different consumptions according to the tasks they perform, and as such, a demand profile can be evaluated.

Most IoT devices have at least these three units (Odunlade and Granath, 2020):

1) Sensors/Actuators: sensors measure the desired variable (for example: temperature) and actuators take action or give feedback according to the sensed value (for example: green or red light).
2) Processing unit: it is the brain of the device, which rules all the embedded software (for example: microprocessor).
3) Communication unit: it is the module in charge of sending data by means of a communication channel (for example: 3G).

The energy consumption for each device is the summation of all the power consumed by these units. However, these units might be working all at once or in a continuous workflow for some period, but for most IoT devices, they spend most of the time shut down with the minimum efforts required. Therefore, IoT devices have different modes of functioning. Although one IoT device may have many modes, these can be grouped into two major categories:

1) Active/awake mode: it represents all the moments in which the device is actively performing the tasks for which it was designed for, which can be summarized as sensing and data sending. As an analogy with computers, it is like when a computer is functioning with the user doing tasks.
   Usually, once the IoT device is awake, the workflow is the following:

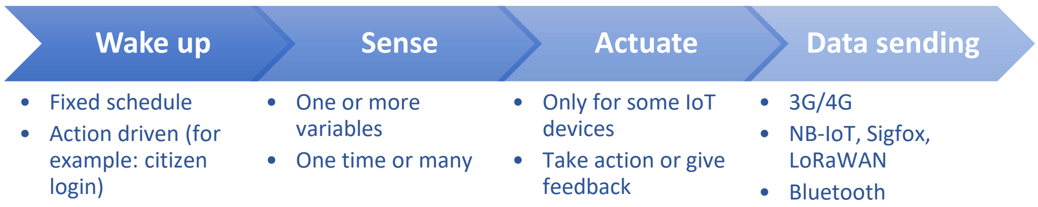


Figure 5. General workflow in Awake mode for IoT devices

2) Sleep mode: most of the time, IoT devices are asleep. This means that they have the minimum required functioning to be able to wake up when needed while reducing consumption as much as possible. In comparison with a computer, it would be like the Suspended/hibernating mode.

In most IoT devices, the sleep mode requires much less power, but it consumes most of the energy as it is the mode in which the devices are most of the time. As a conclusion, it can be said that peak consumption is associated with Active mode, while the Sleep mode represents the base load.

To understand the previous statements with numbers, the consumption profile for RecySmart and Single Sensor will be analyzed.

4.1.1.1 RecySmart device demand analysis

As a reminder, this is how RecySmart device works:

1) The citizen logs in to *RecySmart device* with the smartphone's bluetooth (via *RecySmart citizen app*) or RFID card.
2) Connection is established and the citizen can start.
3) The citizen throws the items one by one. After each recycling action, the device gives feedback with a led light and a sound to the citizen to inform whether the action was correct or not.
4) The information of this recycling process is sent to the servers. Currently, RecySmart sends the data via Bluetooth to the smartphone of users, and the smartphones send the data to the servers.

Then, when RecySmart is in active mode, there are some differences with the standard workflow (Figure 5). The main difference relies on the fact that in one recycling session, there might be multiple recycling actions, each of them having sensing, processing, actuating and data sending. Other difference is that, depending on the way that citizens log in, the final stage will be either data sending (when logged with BLE) or storing the data until next citizen logs in with BLE (when current citizen logs with RFID card).

In average, one recycling session lasts 20 seconds, and in the pilot trial being held at Sant Cugat, there are in average 14 sessions per day. This means that the active mode works only 280 seconds in a day, which is 0.32% of the day.

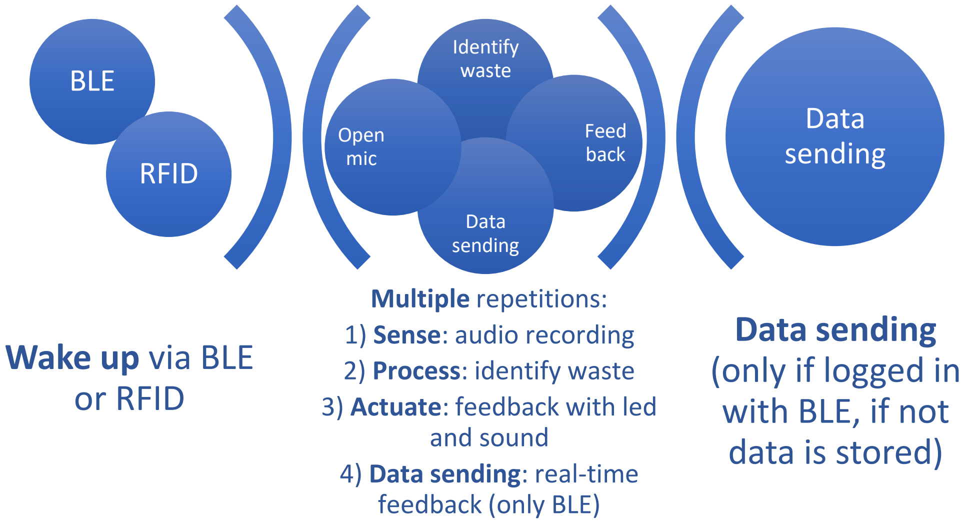


Figure 6. Workflow in Active mode for RecySmart device (recycling session)

RecySmart device uses three Li-$SOCl_2$ batteries of 3.6 V connected in parallel. Moreover, when sensing the current in active and sleep mode, the average values for each mode are 150 mA and 8 mA respectively. Therefore, the energy consumed per day in active mode is 42 mWh/day and in sleep mode is 689 mWh/day. In terms of energy consumption, the active mode represents only 5.75%. Table 5 lists the values for average current, instant power, time per day and energy per day for both modes in RecySmart device. In Figure 7, an hourly demand profile is shown. For simplification, it is being consider that the 14 recycling sessions occur one per hour between 8 and 21 hours. Nevertheless, the total daily consumption would be the same without that exact distribution, and in any case, the monthly consumption would be the same if it is not true that every day has the same amount of recycling sessions.

Table 5. Variables comparison for active and sleep modes in RecySmart

RecySmart			
Variable	Units	Active mode	Sleep mode
Voltage	V	3.6	3.6
Av. Current	mA	150	8
Instant power	mW	540	28.8
Time per day	sec	280	86,120
	%	0.3%	99.7%
Energy per day	mWh	42	689
	%	5.7%	94.3%

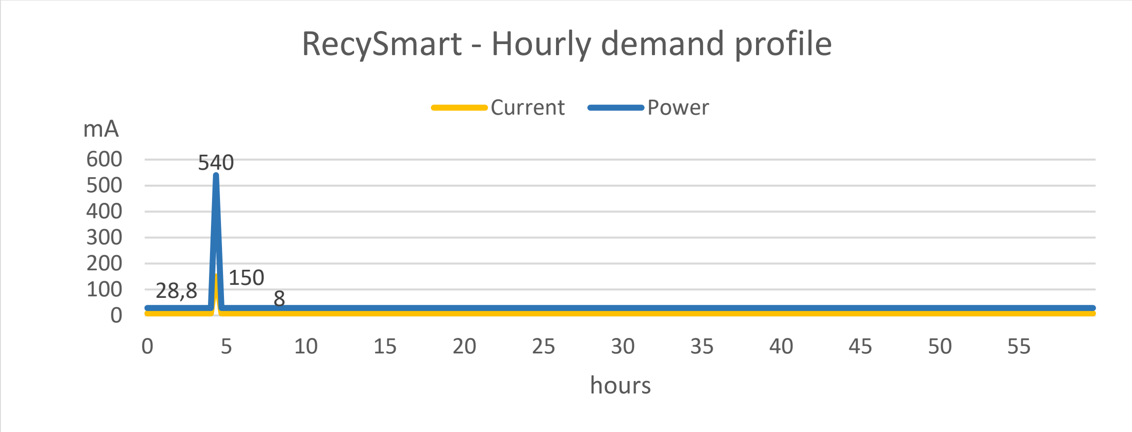


Figure 7. Hourly demand profile for RecySmart (from 8 to 21)

4.1.1.2 Single Sensor demand analysis

The Single Sensor by Sensoneo (and most of ultrasonic sensor) has the typical workflow (Figure 5) of IoT devices in active mode. Although they have some special functionalities to send signals under particular conditions (high T, much tilting, etc.), they basically measure and send data 3 times per day, every 8 hours. The frequency can be adjusted, but three times is the most used. Therefore, the sensor is always asleep except for the three times it has to measure the filling level volume and send it to the servers. Table 6 shows the simplified variables for the Single Sensor.

Table 6. Variables comparison for active and sleep modes in Single Sensor

Single Sensor			
Variable	Units	Active mode	Sleep mode
Voltage	V	3.6	3.6
Av. Current	mA	15.8	0.018
Instant power	mW	56.88	0.065
Time per day	sec	40	86,360
	%	0.0%	100.0%
Energy per day	mWh	0.63	1.55
	%	28.9%	71.1%

The sleep mode has such low average current (18 µA) that it makes the active mode represents in percentage more than that for RecySmart.

It can be seen that its consumption in both modes is much lower than that of RecySmart. This is for two reasons:

a) Single Sensor system is much simpler with less actions and working under a schedule. RecySmart needs to wait and be ready for when a citizen approaches, meaning that both bluetooth and NFC modules are "listening". Also, RecySmart measures and needs to process internally the measurement to give instantaneous feedback.
b) RecySmart is still under constant improvement and has a lot of space to reduce the consumptions in both states (the SW embedded engineers are working on this now that a considerably stable workflow was achieved). For the Single Sensor, the average current of its active mode is near to the average current in RecySmart for sleep mode.

4.1.1.3 Base load approach

As a conclusion of the demand analysis, the proposal will be to design a strategy to cover the base load (sleep mode) as it represents more than 70% for Single Sensor and more than 90% for RecySmart of energy consumption.

Another reason for doing this is that the difference between sleep and active modes is so huge (x20 in RecySmart, x1000 in Single Sensor) that separating strategies might be convenient.

Therefore, the main focus for the technical assessment will be to cover base loads of the IoT devices, and leaving room for alternatives for peak support.

4.1.2 Solar photovoltaic

4.1.2.1 Conventional solar modules

Taking into consideration the large amount of solutions for this technology that there are in the market, the technical assessment will be done by picking one existing solution without the need of much sizing calculations. Also, it is convenient because most suppliers of solar panels for IoT also provide a battery pack compatible with solar charging.

By looking the solutions of Voltaic (Voltaic Systems, 2021), there are mini panels starting with 0.3 W, 2 V to panels 9 W, 18 V.

The 1 W 6 V solar panels is good enough for the needs of RecySmart device and has a relatively small size: 8.9 x 11.3 cm. The output characteristics are the following:

- Open Circuit Voltage: 7.7V
- Peak Voltage: 6.5V
- Peak Current: 180mA
- Peak Power: 1.2W
- Power Tolerance: +/-10%

Analyzing the sunshine hours throughout the year for Barcelona and Stockholm, this solar panel can produce the required energy for RecySmart, considering both active and sleep modes, in both cities all the year. For Barcelona, it can generate from 609% (December) to 1368% (July) of the total needs, while for Stockholm, it can reach 114% (December) to 1450% (June).

Table 7. Generation analysis with Voltaic's 1 W 6 V for Barcelona and Stockholm. Average daily sunshine hours obtained from Agencia Estatal Meteorológica for Barcelona (State Meteorological Agency -Spanish Government, 2021), ClimateTemps for Stockholm (ClimaTemps.com, 2021).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Barcelona													
Average daily sunshine (hs)	4.8	5.71	6.45	7.33	7.87	8.73	10	9.09	7.3	5.8	4.86	4.45	**6.9**
Daily generation (Wh)	4.8	5.71	6.45	7.33	7.87	8.73	10	9.09	7.3	5.8	4.86	4.45	**6.9**
Daily consumption (Wh)	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	**0.73**
Generation/consumption	657%	781%	882%	1003%	1077%	1194%	1368%	1244%	999%	793%	665%	609%	**944%**
Stockholm													
Average daily sunshine (hs)	1.32	2.68	4.87	6.93	9.42	10.60	9.50	8.00	5.80	3.32	1.37	0.83	**5.40**
Daily generation (Wh)	1.32	2.68	4.87	6.93	9.42	10.60	9.50	8.00	5.80	3.32	1.37	0.83	**5.40**
Daily consumption (Wh)	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	**0.73**
Generation/consumption	180%	367%	666%	949%	1288%	1450%	1300%	1094%	793%	454%	187%	114%	**739%**

The excess generation during sunshine hours needs to be stored for use during the night. Different that with households or power plants, in IoT devices the aim is not to maximize energy output but to ensure minimum functioning. Therefore, instead of tilting the panel at the angle in which it can generate more energy at the end of the year, it is more convenient to tilt more towards a favorable angle for winter (more “vertical”) to ensure better capture of irradiation when the resource is less available.

Voltaic has a battery pack kit compatible with the 1 W solar panel with interesting features for IoT devices. This battery will be analyzed in the section of secondary cells.

After having conversations with the supplier and receiving advice from them, the recommendation for Southern Europe was that both 1 W and 2 W would be enough to cover the daily 0.73 Wh. However, for doing so, the panel needs to be combined with batteries. For theirs, then the 2 W is more suitable as the battery pack they offer adds a 7 mA standby current (26 mW) for supplying “Always On” mode, which would be analyzed in the section of secondary cells. Therefore, the proper panel would be the 2 W 6 V panel of size 13.6 x 11.2 cm and the following output characteristics:

- Open Circuit Voltage: 7.7V
- Peak Voltage: 6.5V
- Peak Current: 340mA
- Peak Power: 2.2W
- Power Tolerance: +/-10%

4.1.2.2 Dye-sensitized PV solar cell modules

To begin with, it is important to remark Voltaic’s feedback in regards to DSSC modules. The COO of the company, expert in the field, mentioned that historically DSSC panels used to have much lower performance than normal PV panels, and that the lifetime was also considerably lower.

The company Fujikura provided the energy budget calculations for both IoT devices studied in this MSc Thesis. In Figure 8, the energy budget calculations for RecySmart are shown, considering both Active ("Operative" in the figure) and Sleep ("Standby" in the figure) modes.

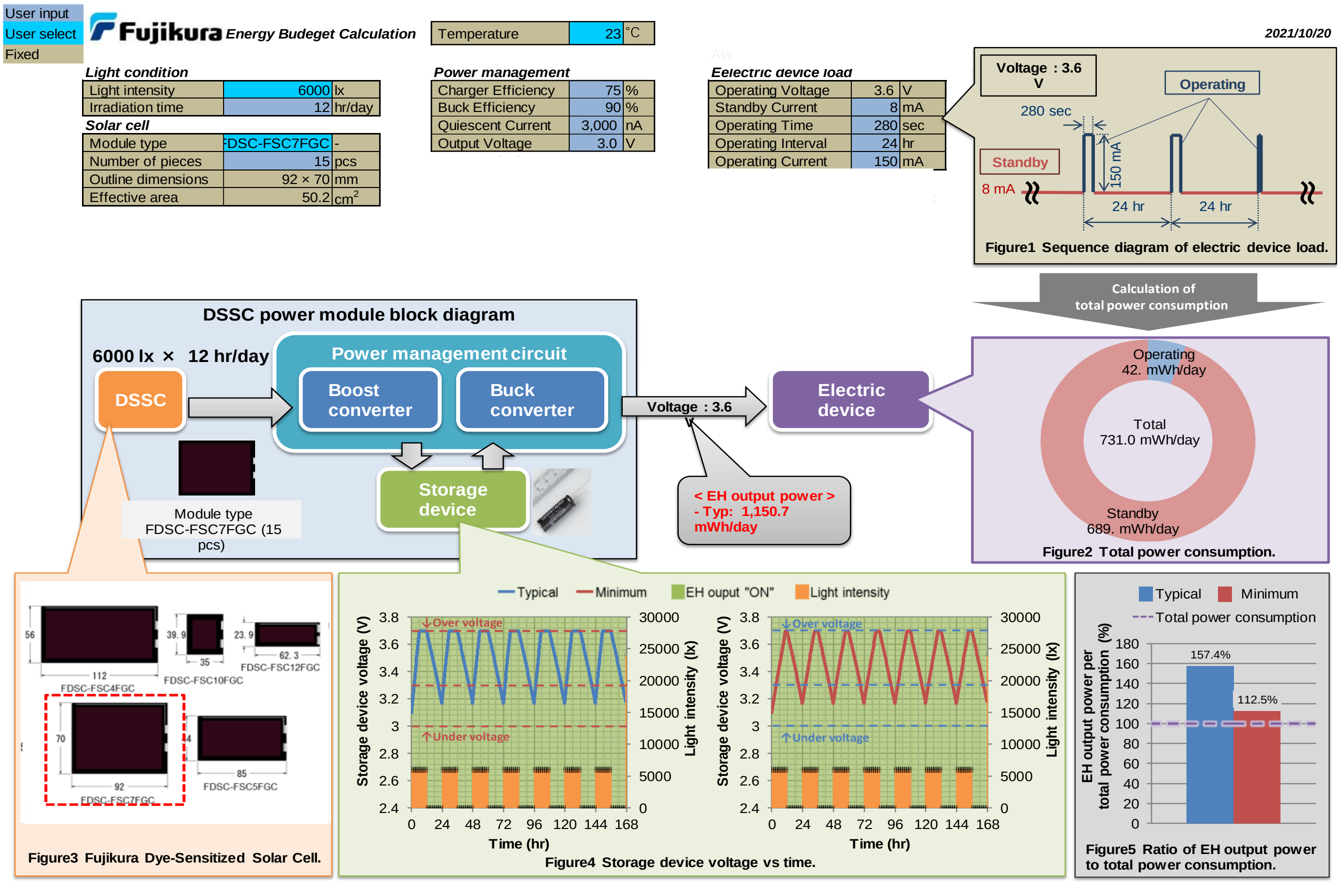
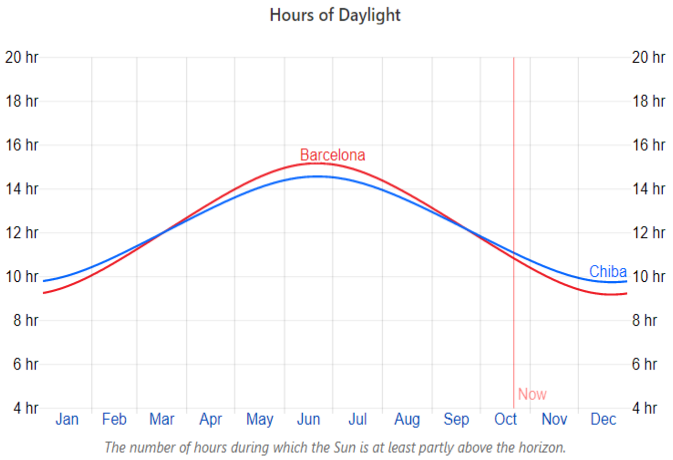


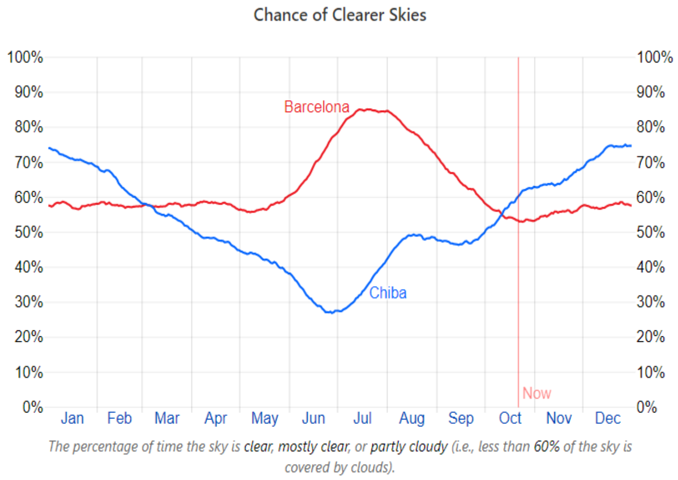
Figure 8. Energy budget calculation and scheme for RecySmart (Fujikura, 2020)

The supplier recommends 15 units of FDSC-FSC7FGC for power supply of RecySmart, considering the conditions of 6000 lx during 12 hr/day illuminance condition. As a reference, Fujikura's technicians are using real data from a building in Chiba, Japan. The mentioned conditions correspond to the brightness in the north side of a building (shady side as it is in the north hemisphere), at almost ground level, in September on a typical cloudy day.

To compare with Barcelona, Chiba is almost at the same latitude, and in overall Spanish sky is in average clearer. A comparison done among Chiba and Barcelona in WeatherSpark.com (Weather Spark, 2021) shows that Barcelona's conditions will be more favorable than those included in this analysis, as can be seen in the set of graphs in Figure 9.



Daylight	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Barcelona	9.6h	10.7h	12.0h	13.4h	14.6h	15.1h	14.8h	13.7h	12.4h	11.0h	9.8h	9.2h
Chiba	10.1h	10.9h	12.0h	13.1h	14.1h	14.5h	14.3h	13.4h	12.4h	11.2h	10.3h	9.8h



Clearer Skies	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Barcelona	58%	58%	58%	58%	57%	69%	84%	78%	64%	55%	56%	58%
Chiba	71%	64%	55%	48%	42%	31%	34%	48%	48%	58%	65%	73%

Figure 9. Comparison of hours of daylight (left) and chance of clearer skies (right) between Barcelona and Chiba (Weather Spark, 2021)

In the calculations, Fujikura also considered different scenarios of illuminance and irradiation times to establish thresholds between good combinations and non-good combinations for these variables for the proposed array of 15 FDSC-FSC7FGC. In Figure 10 the different combinations and their categorization can be seen.

FDSC-FSC7FGC (15pcs)

	Irradiation time (hr/day)				
lx	2	4	8	12	24
100	◆	◆	◆	◆	◆
200	◆	◆	◆	◆	◆
300	◆	◆	◆	◆	◆
400	◆	◆	◆	◆	◆
500	◆	◆	◆	◆	◆
600	◆	◆	◆	◆	◆
700	◆	◆	◆	◆	◆
800	◆	◆	◆	◆	◆
900	◆	◆	◆	◆	◆
1000	◆	◆	◆	◆	◆
1500	◆	◆	◆	◆	◆
2000	◆	◆	◆	◆	△
2500	◆	◆	◆	◆	○
3000	◆	◆	◆	◆	○
4000	◆	◆	◆	△	○
5000	◆	◆	◆	△	○
6000	◆	◆	△	○	○
Over 10000	◆	◆	○	○	○

Figure 10. Irradiation time and illuminance combinations: good (green), threshold zone (yellow), non-good (red) (Fujikura, 2020)

Regarding the array, the best combination for the 15 pieces is 3 rows and 5 columns, as shown in Figure 11, with dimensions would be 350 x 276 mm. However, for some models of waste bins, a different array could be proposed.

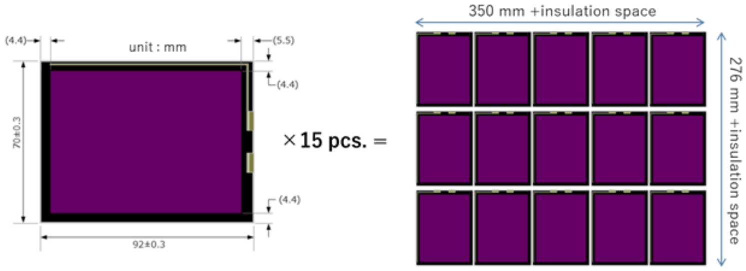


Figure 11. Proposed array for 15 pieces (Fujikura, 2020)

The typical values for the electrical specifications for one piece under 200 lx (white LED) and 23ºC are:

- Maximum power: 340 µW
- Operation current: 796 µA
- Open circuit voltage: 0.58 V

Apart from the modules, Fujikura recommends having a 3.6V-160 mAh, or more, of energy storage to cover the night time power consumption. According to their calculations, the energy harvester output power can exceed the total power consumption in 12.5% in the worst case and 57.4% in a typical case.

For the Single Sensor, Fujikura recommends only one unit of FDSC-FSC5FGC, which has a smaller size (37.4 cm^2 – 4.4 x 8.5) which could be easily placed above the sensor (on the outside part of the top of the bin). The illuminance condition assumed in the calculations is 500 lx (assimilable to the ambient illumination at sunrise or sunset on a clear day) during 12 hr/day. Then, the recommended storage should have at least a capacity of 0.6 mAh and 3.6 V to cover the power consumption of one day. The calculations and schemes can be seen in Figure 12 and the combinations of irradiation time and illuminance in Figure 13.

The typical values for the electrical specifications for one FDSC-FSC5FGC under 200 lx (white LED) and 23ºC are:

- Maximum power: 165 µW
- Operation current: 425 µA
- Open circuit voltage: 0.50 V

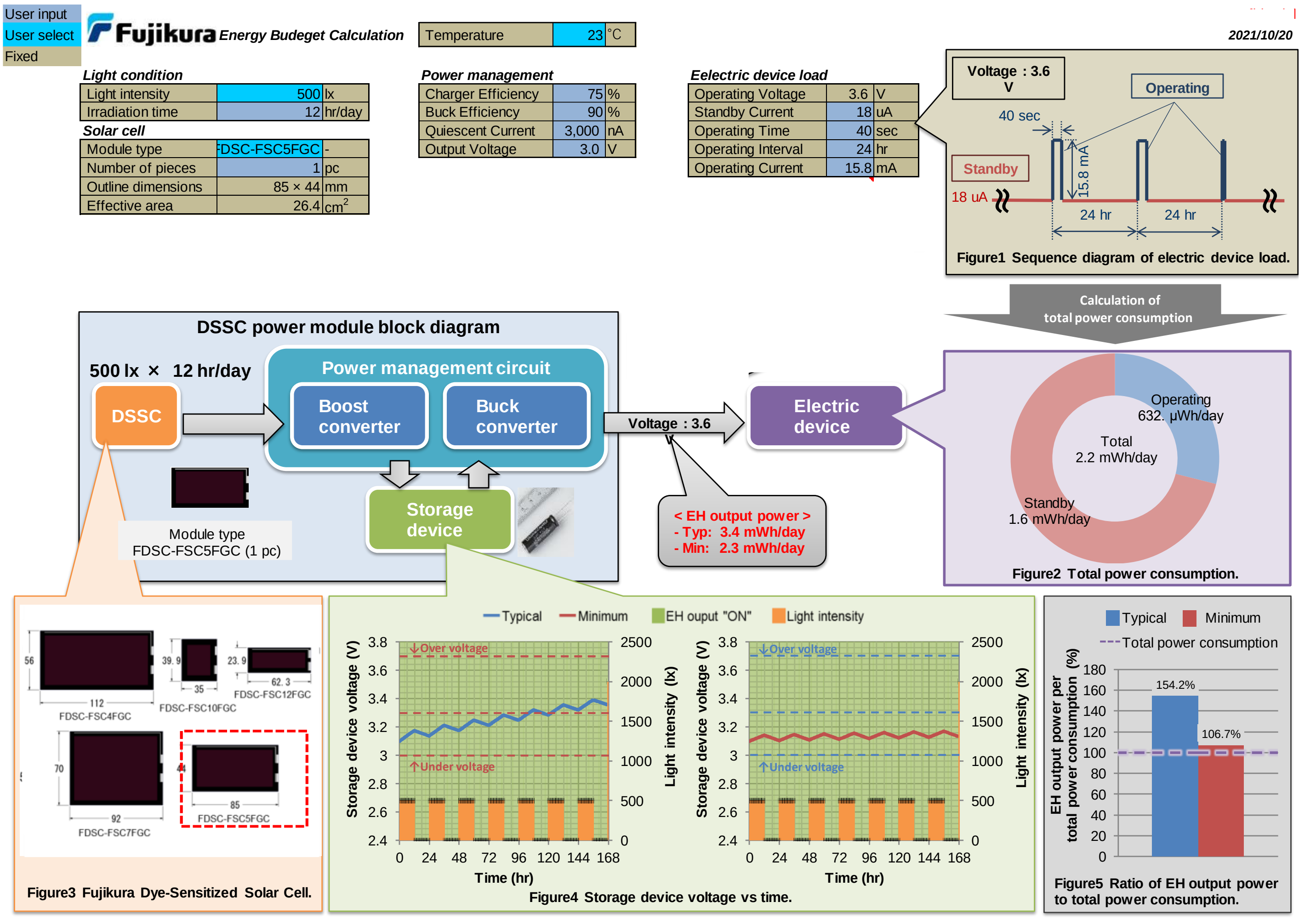


Figure 12. Energy budget calculation and scheme for Single Sensor (Fujikura, 2020)

FDSC-FSC5FGC (1pc)

	Irradiation time (hr/day)				
lx	2	4	8	12	24
100	◆	◆	◆	◆	◆
200	◆	◆	◆	◆	△
300	◆	◆	◆	◆	○
400	◆	◆	◆	△	○
500	◆	◆	◆	○	○
600	◆	◆	△	○	○
700	◆	◆	○	○	○
800	◆	◆	○	○	○
900	◆	◆	○	○	○
1000	◆	△	○	○	○
1500	◆	○	○	○	○
2000	△	○	○	○	○
2500	△	○	○	○	○
3000	○	○	○	○	○
4000	○	○	○	○	○
5000	○	○	○	○	○
6000	○	○	○	○	○
Over 10000	○	○	○	○	○

Figure 13. Irradiation time and illuminance combinations for one piece of FDSC-FSC5FGC (Fujikura, 2020)

4.1.3 Fuel cells

Among fuel cells company, there are not many solutions specially designed for IoT as with PV technologies. Neither it does not seem that there are widely accepted fuel cells for portable devices. Besides, it seems that for portable uses and small scale, most are based on fuel cartridge replacement. Nevertheless, there are some products (reversible fuel cells) that can fit the needs with a certain level of adjustment.

There is a set of fuel cells that, despite they are intended only for educational purposes, they have adequate characteristics for the application studied (Fuel Cells Store, 2021). These FCs will not be analyzed as a direct opportunity to incorporate into the IoT devices, but will be used as reference to understand the technicalities for this study.

There is a Double Reversible Fuel Cell (H-Tec Education, 2019) that can work with H_2 and O_2 or air when operating in fuel cell mode, and with distilled water when making the reverse process (electrolysis of water). When working with oxygen, two storage tanks are needed (one for H_2 and one for O_2), while when operating with air, only one tank is needed for the hydrogen.

The DRFC has a rated power (fuel cell mode) of 1000 mW (750 mA) when working with pure oxygen and of 400 mW (300 mA) when working with air. When operating in electrolyser mode, the gas productions are 20 ml/min for H_2 and 10 ml/min for O_2, and the permissible power input is 5.5 W (1.5 A). This DRFC would not be compatible with the previous analyzed solar panel as it would not supply the power and current needed, as it had rated power 1 W with peak current of 180 mA, unless power electronics are used in between.

The size of the fuel cell is 56 x 42 x 57 mm (H x W x D). The size of the storage tanks is 90 x 55 x 40 mm (H x W x D) each, with capacity to hold 30 cm^3 of gas and additional 30 cm^3 for water.

Overall, the size of the array would be acceptable. It would be more suitable to incorporate it in a specially built bin rather than in a standard urban waste bin. The reason for this is that the last ones are not designed to hold this infrastructure, and embedding the fuel cell and storage tank into the RecySmart device would mean duplicating its current size. For a Single Sensor, this array would be quite large because Single Sensors are always intended to be deployed in standard waste bins.

Another challenge relies on the reversibility. According to the specifications, it is not guaranteed that the process can be reversed multiple times. On the contrary, the manufacturer advises to refill with distilled water for each operation and warns that hydrogen leakages may occur. This is a known issue when dealing with this gas due to its low density that makes it easy for the particles to escape. Latest developments used nanomaterial technology for retaining H_2, while the storage tank provided in this kit is relatively simple and made of plastic, not ensuring tightness. If the process cannot be reversed multiple times without human intervention, then it might not be as convenient as thought. Although the maintenance would be relatively simple as it only requires filling distilled water, it involves time from an operator to do so. Besides, if reversion is not guaranteed, then there is the risk of the system falling off due to lack of fuel or water.

Other alternatives found among fuel cell suppliers rely on hydrogen storage batteries. These solutions seem to have more alternatives within the market, yet no solution specific for IoT powering was found. The company Horizon Fuel Cells has its own educational vertical (Horizon Educational, 2021) in which they offer kits with micro fuel cells, solar panels and storage tanks (alike H-Tec Education), but also provide portable hydrogen cartridges only for the case of fuel cell operation. The kits in the educational vertical seem nearer to the needs of an IoT device than the rest of their portfolio which is more focused on larger power needs like vehicles.

The fuel cells can operate either by reversing the process by means of electrolysis powered up by an external power source (solar panel) or by supplying external fuel (H_2 cartridge).

The Hydrostick Pro cartridge has inside a AB2 alloy for hydrogen absorption by forming a solid metal hydride. This way of storing H_2 removes the need of compressing the hydrogen thus reducing risks and avoiding leaks. According to the supplier, the Hydrostik Pro can be stored for much longer time than lithium batteries without drop in performance, and can be recharged up to 100 times, making them equivalent to 1000 non-rechargeable AA batteries. The cartridge can be replaced by a new one or refilled with the Hydrofill Pro by Horizon Educational, which is basically an electrolyzer that serves as refueling station on demand (with electricity supply and distilled water).

Regarding power supply, the cartridge can provide 10 hours of continuous consumption of 1W. This means, that a cartridge supplies 10 Wh. However, it would be necessary to confirm with the supplier if the supply rate can be managed to be that needed for the IoT device. For example, for RecySmart device it was calculated that 731 mWh is the daily consumption, therefore, if the supply rate could be controlled and matched with the consumption, one cartridge could last 15 days covering only sleep mode consumption or 13.7 days covering all consumption. For Single Sensor, according to the calculations, a cartridge could last for 12.56 years. However, due to different reasons, this number will probably be less.

The replacement of the cartridge could be done by the operators in the waste collection rounds or by other cleaning and maintenance operators that are circulating constantly in the street. This of course would add extra time to operations and increase OPEX, but this will be analyzed later on in the economic assessment.

Another point to be assessed directly with the manufacturer is the possibility to recharge the cartridge directly with a reversible fuel cell in electrolysis mode, but probably a compressing unit would be needed to inject the hydrogen gas into the cartridge.

In conclusion, it seems the alternative of using conventional fuel cells might not be optimal for Single Sensor as the size of the power supply would almost double the size of the device, while also complicating the functioning of the device. Also, because of the positioning of the Single Sensor in the top of urban bins and from the inside part, the replacement of cartridge would not be easy for the operator in charge. As for RecySmart device, it might be an option but development would be needed. There is not a solution that is technically feasible as a plug-and-play solution to acquire in the market today.

Nevertheless, there is being huge development of bioenzymatic fuel cells from the French start-up BeFC (BeFC, 2021), and probably from others, which appears to be a promising and sustainable solution for low-power electronics. These fuel cells avoid the use of toxic metals as catalysts as they replace them with enzymes, and they can generate from 1 to 2.5 mW per cm^2. In conversation with Jules Hammond, CEO of BeFC, he recommended that their solution might not be the best fit for the power consumption of RecySmart, as too many replaces would be needed (at least once every 6 months). However, for Single Sensor it can be a good alternative if the technology continues to improve. The main interest of this technology is that it reduces environmental imapct considerably, to be assessed in the environmental analysis for solutions.

4.1.4 Secondary cells

The most straightforward way of analyzing rechargeable batteries would be to look for existing models that have similar characteristics than the currently used batteries. In Table 8 the main rechargeable battery technologies are compared. In this table, the only technology that is not commonly used for portable devices and IoT devices is lead acid, and reusable alkaline is not the most used currently. Then, in Table 9, a summary of advantages and disadvantages is shown for the most used small rechargeable battery types.

Table 8. Characteristics of six most used rechargeable batteries (Battery University, 2017)

	NiCd	***NiMH***	***Lead Acid***	***Li-ion***	***Li-ion polymer***	***Reusable Alkaline***
						
Gravimetric Energy Density *(Wh/kg)*	45-80	60-120	30-50	110-160	100-130	80 (initial)
Internal Resistance *(includes peripheral circuits) in mΩ*	100 to 200 6V pack	200 to 300 6V pack	<100 12V pack	150 to 250 7.2V pack	200 to 300 7.2V pack	200 to 2000 6V pack
Cycle Life *(to 80% of initial capacity)*	1500	300 to 500	200 to 300	500 to 1000	300 to 500	50 (to 50%)
Fast Charge Time	1h typical	2-4h	8-16h	2-4h	2-4h	2-3h
Overcharge Tolerance	moderate	low	high	very low	low	moderate
Self-discharge / Month *(room temperature)*	20%	30%	5%	10%	~10%	0.3%
Cell Voltage *(nominal)*	1.25V	1.25V	2V	3.6V	3.6V	1.5V
Load Current *- peak - best result*	20C 1C	5C 0.5C or lower	5C 0.2C	>2C 1C or lower	>2C 1C or lower	0.5C 0.2C or lower
Operating Temperature *(discharge only)*	-40 to 60°C	-20 to 60°C	-20 to 60°C	-20 to 60°C	0 to 60°C	0 to 65°C
Maintenance Requirement	30 to 60 days	60 to 90 days	3 to 6 months	not req.	not req.	not req.
Typical Battery Cost *(US$, reference only)*	$50 (7.2V)	$60 (7.2V)	$25 (6V)	$100 (7.2V)	$100 (7.2V)	$5 (9V)
Cost per Cycle *(US$)*	$0.04	$0.12	$0.10	$0.14	$0.29	$0.10-0.50
Commercial use since	1950	1990	1970 (sealed lead acid)	1991	1999	1992

The relevant factors to be considered for the election of a rechargeable battery are (Saurav, 2018):

- Nominal voltage: the least voltage at which the device will operate. The chosen battery must have a minimum voltage rating that either is equal to the device's nominal voltage or is lesser than that.
- Operating duration of the device.
- The number of times the battery can be recharged, retention of charge and response to trickle charge has to be taken into consideration to decide the life of the battery.
- Cut off voltage is important to know the end of battery charge. Knowing the cut off voltage, a circuit that disconnects the battery when it has reached that value can be easily implemented.
- Physical characteristics of the battery are also important.
- Environmental considerations to take into account are battery's ability to reject moisture, corrosion, overheating, bloating, withstand shock and damage.
- Cost

Table 9. Summary of main advantages and disadvantages for different rechargeable batteries (Saurav, 2018)

Battery Type	**Image**	**Characteristics**
Nickel Cadmium		Fast, simple charge, a higher number of charge-discharge cycles, relatively low energy density, suffers from the memory effect – High Self Discharge (15 %/month)

Nickel-Metal Hydride		Higher storing capacity, lesser memory effect problem, environment-friendly, limited discharge current – High Self Discharge (30%/month)
Lithium-Ion		High energy density, relatively low self-discharge, low maintenance, requires voltage and current protection circuit, aging effect – Medium Self Discharge (3%/month)
Lithium-Ion Polymer		Flexible form factor, lightweight, lower energy density, less life cycle
Lithium Cobalt		Expensive, high specific energy density, limited specific power
Lithium Manganese		Less capacity, high power, used in medical devices and electric powertrains

Overall, there are so many available options for rechargeable batteries and suppliers that finding a good fit for the needs of the device should be easy. It requires a good evaluation of available options and discussion with the different distributors or manufacturers.

4.1.4.1 Nickel metal-hydride

The Chinese company Greepow (Grepow, 2021) designs and manufactures different types of rechargeable batteries - Lithium polymer (LiPO), Nickel metal-hydride (Ni-MH), and Lithium iron phosphate (LiFePO4) of multiple sizes, shapes (even customizable) and characteristics.

Within their portfolio of NiMH batteries, Grepow has sized D and cylindrical batteries with similar dimensions than the current batteries used for RecySmart. That would allow the possibility of introducing rechargeable batteries within the same spacing that the electronic box has for the current batteries. However, same changes into the mother should be done as some power electronics are needed to control charging, discharging, voltage, etc.

Table 10. Comparison between current batteries and rechargeable NiMH batteries for RecySmart

Type	Primary	Secondary
Chemistry	Li-SOCl2	NiMH
Model	ER34615	-
Brand	Fullwat	Grepow
Voltage [V]	3.6	1.2
Capacity [Ah]	19	5 to 10
Shape	Cylindrical	Cylindrical
Size	D	D
Height [mm]	61.5	61.0
Diameter [mm]	Ø33.1	Ø32.2
Weight [g]	100	102.5 to 174
Temp. range [ºC]	-60 to 85	Varying

Table 11. Comparison between current batteries and rechargeable NiMH batteries for Single Sensor

Type	Primary	Secondary
Chemistry	Li-SOCl2	NiMH
Model	LS14500	-
Brand	Saft	Grepow

Voltage [V]	3.6	1.2
Capacity [Ah]	2.6	1.8
Shape	Cylindrical	Cylindrical
Size	AA	AA
Height [mm]	50.0	50.4
Diameter [mm]	Ø14.4	Ø14.1
Weight [g]	16.7	27
Temp. range [ºC]	-60 to 85	Varying

The NiMH batteries have series according to their use which can be high power, wide temperature range, low self-discharge, high-temperature, low-temperature. According to the location where the devices would be placed, a different type of series could be selected.

Although there are very good matches in sizes for batteries for both devices and the capacity of the rechargeable cells would be good enough (as it can be recharged), there is the disadvantage that NiMH works under lower voltages. This can be corrected with power electronics but the changes should be carefully studied by the technical team at Recircula Solutions. Other option is to place 3 batteries in series to reach a 3.6 V, but this may need addition of parallel branches to charge each battery independently. In general, NiMH batteries have life cycles of 180 to 2,000 cycles (Saurav, 2018).

4.1.4.2 Lithium-ion polymer

Lithium Ion Polymer (LiPo) batteries are the most common type of batteries currently used in day to day life. These are special for being able to work under different shapes. The voltage of LiPo depends on the chemistry of the battery, but generally they have nominal voltage of 3.6 V. In general, one of the main drawbacks of these batteries is that they are affected by overcharge, over-discharge, very high temperatures, short circuit, etc. which causes it to either bloat, leak or catch fire. Therefore, power electronics should be included for safety and prolonging lifetime.

Grepow has developed LiPo batteries that, not only solve some of the common issues associated to this type of batteries, but also that can be customized in shape. The customization in shape is quite useful for Recircula's IoT devices because the battery is designed to fit the device and not the other way. In RecySmart's roadmap, it is contemplated to have a newer version in which the mechanical design conserves only the ring without the electronic box. For this, the HW engineer is designing modular PCBs to be placed within the frame of the ring, and with a semicircular shaped battery, it would be easier to fit. On the contrary, shaped battery make clients more dependent on Recircula's supplying capacity (and Grepow's capacity), while using universal batteries make it easier to find fast replacement in various parts of the world. Besides, there seems not to be a cilindrical option, so the current holders and connections for batteries should be changed if LiPO are to be used. Another option would be Grepow's button-like LiPo batteries that are easy to mount in small spots. Finally, the highlighted features for all Grepow's LiPo batteries are:

1. Excellent explosion-proof performance, no fire or explosion in gun test.
2. Any shape, according to the actual product application requirements
3. Thickness: 0.4~8 mm; width: 6~50 mm.
4. Support high rate discharge, fast charging capacity.
5. Wide operating temperature: -50 to 50ºC or -20 to 80ºC

Considering the spacing that current batteries use in RecySmart device, there are approximately 198 cm^3 (H 100 mm x L 60 mm x W 33 mm). Therefore, there are rectangular LiPo batteries that could fit this same space. Grepow has more than 160 models for rectangle shape LiPo batteries, so the offer is more than enough. Looking into the dimensions and capacities, model GRP5930060 could be a good fit (prioritizing space), with the following specifications:

- Fully charged voltage: 4.2 V
- Nominal voltage: 3.7 V
- Discharge rate: 15 C
- Capacity: 1,000 mAh
- Energy density: 349 Wh/L – 180.5 Wh/kg
- Weight: 20.5 g
- Thickness: 5.7 mm
- Width 30.0 mm
- Length 62.0 mm

Regarding the capacity and discharge rate (1000 mAh * 15 C = 15,000 mAh), it can be said that the battery can supply continuously 15,000 mA, which is more than enough, oversized in fact.

Considering RecySmart sleep mode's current of 8 mA and a depth of discharge up to 20%, then one full charge (80%) could run the device in sleep mode for 100 hs (4.16 days) without recharge.

As for the charging rate, Grepow declares that its rectangular LiPo batteries have fast charging at 3C or even 5C. Therefore, taking 3C and respecting the 20% depth of discharge, the recharge can happen at a maximum current of 3,000 mA. Taking as an example Voltaic's 2 W 6 V panel, it has a peak current of 340 mA.

Moreover, considering the size of the mentioned model, there is space for 15 units (scheme of maximum possible array in Figure 14), which would however mean oversizing the power supply unit. Besides, a LiPo charger should be also considered in the spacing, but still 15 units would be oversizing unnecessarily. Taking as an example of Fujikura's recommendation, a 160 mAh storage device would be enough to cover night time consumption with their DSSC modules, so one unit would be enough.

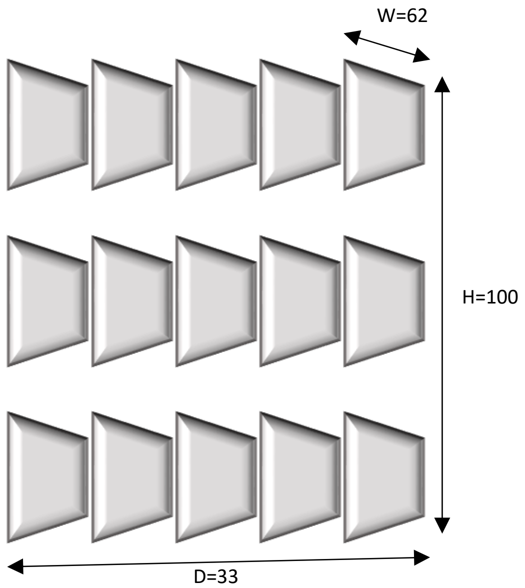


Figure 14. Possible maximum fitting array scheme of 15 LiPo batteries into current space for power supply in RecySmart

4.1.4.3 Li-ion

For Li-ion batteries, there are multiple customized battery packs in the market. It might be convenient to use the same supplier both for energy harvesting devices and storage solutions as this brings more reliability in the full pack which is studied all by the same technicians, as well as simplifying operations and negotiations. Therefore, Voltaic's V25 battery pack will be studied (Li-ion based) as it was recommended to work with the selected panel.

The V25 USB Battery Pack has 6,400 mAh capacity and was specially designed for combination with solar power for the applications of wearables, portable devices (smartphones, cameras, tablets), IoT devices and microcontrollers. It has an "Always On" feature that ensures that the output of the power bank does not shut off after a certain period of time. Basically, it stays on to support Sleep mode. As a drawback, this adds a self-consumption current of the battery bank of 7 mA (26 mW), that should be added to the Sleep mode consumption of 8 mA. The "Always On" mode was designed to power devices for several days to months without human intervention.

The specifications for V25 USB Battery Pack are:

- Size: 7.7 x 7.8 x 2.6 cm
- Weight: 160 gr
- Capacity: 6,400 mAh, 23 Wh
- Output: 5V/2A, 3A max (2 outputs)
- MicroUSB Input: 5-6V/2A
- Minimum charge current: 5mA
- Maximum power point: 5.2V
- USB-C (Input only): 5V/2A
- Battery type: Li-ion
- Protection: Short circuit over charge, over discharge, over temperature (45ºC input cutoff, 60ºC output cutoff), under temperature (0ºC input cutoff, -20ºC output cutoff)

The main inconvenience with current design of RecySmart is that the output voltage of the battery pack is 5V. Although the device can work under this voltage, all the PCB is designed with nominal voltage of 3.6V. Nevertheless, it might imply some power electronics adjustment from the technical team side but should not be a stopper.

Table 12. Generation and storage analysis with Voltaic's 2 W 6 V for Barcelona and Stockholm

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Barcelona													
Average daily sunshine (hs)	4.8	5.71	6.45	7.33	7.87	8.73	10	9.09	7.3	5.8	4.86	4.45	**6.9**
Daily generation (Wh)	9.6	11.42	12.9	14.66	15.74	17.46	20	18.18	14.6	11.6	9.72	8.9	**13.8**
Daily consumption (Wh)	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	**0.73**
Available for storage (Wh)	8.87	10.69	12.17	13.93	15.01	16.73	19.27	17.45	13.87	10.87	8.99	8.17	**13.07**
Storage capacity (Wh)	23	23	23	23	23	23	23	23	23	23	23	23	**23**
Stored - 90% eff. - (Wh)	7.98	9.62	10.95	12.54	13.51	15.06	17.34	15.70	12.48	9.78	8.09	7.35	**11.76**
Self consumption (Wh)	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	**0.62**
Useful stored (Wh)	7.36	9.00	10.33	11.91	12.88	14.43	16.72	15.08	11.86	9.16	7.47	6.73	**11.14**
Autonomy (days)	10.07	12.31	14.13	16.30	17.63	19.74	22.87	20.63	16.22	12.53	10.21	9.20	**15.24**
Stockholm													
Average daily sunshine (hs)	1.32	2.68	4.87	6.93	9.42	10.60	9.50	8.00	5.80	3.32	1.37	0.83	**5.40**
Daily generation (Wh)	2.63	5.37	9.73	13.87	18.83	21.20	19.00	16.00	11.60	6.63	2.73	1.67	**10.80**
Daily consumption (Wh)	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	**0.73**

Available for storage (Wh)	1.90	4.64	9.00	13.14	18.10	20.47	18.27	15.27	10.87	5.90	2.00	0.94	**10.07**
Storage capacity (Wh)	23	23	23	23	23	23	23	23	23	23	23	23	**23**
Stored - 90% eff. - (Wh)	1.71	4.17	8.10	11.82	16.29	18.42	16.44	13.74	9.78	5.31	1.80	0.84	**9.06**
Self consumption (Wh)	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	**0.62**
Useful stored (Wh)	1.09	3.55	7.48	11.20	15.67	17.80	15.82	13.12	9.16	4.69	1.18	0.22	**8.44**
Autonomy (days)	1.49	4.85	10.23	15.32	21.44	24.35	21.64	17.95	12.53	6.41	1.61	0.30	**11.54**

As can be seen in Table 12, when using a 2W solar panel and considering a charging efficiency of 90% (PowerTech Systems, 2021) and the self-consumption for Always On mode, in the worst conditions (December) it is possible to store enough energy for 9 days in Barcelona but less than 1 day in Stockholm, while in the best summer month for each region it is possible to store enough energy for 23-25 days. In conclusion, for Barcelona the system seems more than robust, while for Stockholm it might be advisable to count on an extra power source due to continuous overcast skies and low temperatures.

4.1.5 Supercapacitors

First, it is important to understand that a supercapacitor is not a replacement for battery for long-term storage. According to Battery University (Battery University, 2021), if the charge and discharge times are more than 60 seconds, then the battery is the suitable storage device, if less then, the supercapacitor might be preferable. Using a hybrid strategy can improve performance when fast charge or discharge are needed and to reduce battery stress. Therefore, supercapacitors are suitable to provide support for active modes.

Due to this, it can be said that rechargeable batteries will be necessary while supercapacitors might be added to improve performance and lifetime. However, having previously studied batteries that could cover even active mode, supercapacitors could be left aside in a first evolution of the devices' power system.

Supercapacitors have low specific energy and are expensive in terms of cost per watt. It is debatable if it would not be a better strategy to directly oversize the battery system to cover peaks and do not include supercapacitors, thus having a simpler system. However, thanks to its almost unlimited cycle life, once the supercapacitor is included then it does not need replacement thus prolonging the life of all successive rechargeable batteries.

Table 13. Advantages and limitations of supercapacitors (Battery University, 2021)

Advantages	Limitations
• Virtually unlimited cycle life (million cycles) • High specific power; low resistance enables high load currents • Charges in seconds; no end-of-charge termination required • Simple charging; draws only what it needs; not subject to overcharge • Safe; forgiving if abused • Excellent low-temperature charge and discharge performance	• Low specific energy; holds a fraction of a regular battery • Linear discharge voltage prevents using the full energy spectrum • High self-discharge; higher than most batteries • Low cell voltage; requires series connections with voltage balancing • High cost per watt

Capacitech's cable-based supercapacitor has a capacity of storing 1.07 mWh and a rated voltage of 1.6 V. For one recycling session of RecySmart, which means a consumption of 3 mWh, it would be necessary to have 3 supercapacitors (in series to boost voltage). For Single Sensor, one CBC would be enough to cover the peaks (when panel is generating).

4.2 ENVIRONMENTAL ASSESSMENT

4.2.1 Solar photovoltaic

4.2.1.1 Conventional solar modules

To begin with, solar photovoltaic technology has in general a good acceptance as it is intended to solve environmental issues. This is mainly because during energy generation, there are no carbon emissions. However, it would not be correct to say that the technology is net-zero. For understanding the environmental impacts of solar PV, the literature in the field will be addressed.

Tawalbeh et al. performed a critical review on the environmental impacts of solar PV systems (Tawalbeh *et al.*, 2021). Even recognizing that PV technology has a carbon footprint of 14-73 g CO_2-eq/kWh which is 10 to 53 times lower than the emissions associated to the burning of oil, there are still many points in which PV panels have considerable environmental impact.

First, and considering only the application studied in this Master thesis, the largest impact of PV modules would come from the use of hazardous materials in the manufacturing process and due to the reduced efficiency in energy harvesting. As mentioned before, PV modules have negligible effect on air pollution and global warming when producing electricity, making the fabrication the largest contributing stage of GHG emissions. For utility scale PV systems, this stage accounts for 71.3% of the total carbon footprint (Nugent and Sovacool, 2014), with transportations accounting only in 0.1% and 1% within the stage (Tsoutsos, Frantzeskaki and Gekas, 2005). For the studied application, the main burden would be that generated when producing aluminium for frames, the glass, and the reduction of silica to silicon for the cells (Alsema and De Wild-Scholten, 2006).

In addition, several raw materials used during PV cells' manufacturing which involve mining, extraction and purification during their production. These are silicon, cadmium, tellurium, copper, selenium and gallium among others. Some become available as by-product from the mining of other minerals, like cadmium or tellurium. Regarding the latter, it is a scarce material so the recovery and recycling is of highly importance for CdTe solar cells' production.

During the production of solar cells, it is not only GHG emissions, but also heavy metals emissions which affect the environment. Besides, various flammable, corrosive, toxic, and carcinogenic chemicals and solvents like, hydrochloric acid, ammonia, and others are used for different stages of the fabrication (Aman *et al.*, 2015).

However, taking into consideration the price drop in the last decade by a factor of 10 of the technology reflects the huge steps the sector as a whole has made, and it could be expected that there will be more advances in the whole value chain with special focus in improving efficiency when harvesting and optimizing the manufacturing and recycling stages. In regards to recycling, although there is still much to do, a lot has already been achieved. Also, 90% of materials in solar modules can be fully recycled (Bogacka, Pikoń and Landrat, 2017; Maani *et al.*, 2020), which motivates new investments for research and development in the field. Only by using recycled silicon material, a reduction of 42% of GHG emissions is possible (Klugmann-Radziemska and Kuczyńska-Łażewska, 2020).

Table 14. SOx, NOx and CO_2 emissions from different PV module types (Engül and Theis, 2011)

		Silcon PVs			Thin film PVs		Nano PVs	
GHG	Unit	Ribbon multi-Si	Multi-Si	Mono-Si	CdTe	CIS	DSPV	QDPV
SO_x	mg/kWh	55	55	65	50	105	195	20
NO_x	mg/kWh	35	40	45	25	35	115	5
CO_2	g/kWh	19	24	28	16	69	59	5

CIS: Copper Indium Selenide, CdTe: Cadmium Telluride, DSPV: Dye sensitized PV, QDPV: Quantum Dot-PV, Multi-Si: Multicrystalline silicon, Mono-Si: Monocrystalline silicon.

4.2.1.2 Dye-sensitized PV solar cell modules

From Table 14, it can be seen that according to Engül and Theis, dye sensitized PV solar cells generate around the triple SO_X emissions, and more than twice NO_X and CO_2 emissions than those generated by mono and multicrystalline silicon solar cells (Engül and Theis, 2011).

As for conventional photovoltaic cells, large part of the environmental impact of DSC is related with the glass substrate, as the manufacturing of glass is highly energy consuming. This can be avoided by using recycled glass, or using thinner layers, or by replacing it by metal or polymer foil substrates (Veltkamp, 2007). However, glass substrates are still used because along with high temperature processing they give much better performance and stability. In contrast, another advantage for metal and polymer foil based substrates is that they might not require the aluminium frame, hence reducing the energy requirement even more.

In addition, the production of the cells itself consumes large amount of energy, especially for the TiO_2 layer sintering and glass-glass lamination. Moreover, the use of silver, platinum and ruthenium increase the environmental burden of DSCs. Ruthenium is an essential part of the most common dye but a scarce material. However, organic dyes are being developed to improve the efficiency and stability without the dependency on ruthenium.

For DSC modules, the energy payback time for North-West Europe is of 1.4 years and for Southern Europe of 0.8 years. Considering that for multicrystalline silicon modules installed on rooftops in Southern Europe the EPBT is 1.5, then it can be said that DSC present an advantage against conventional PV cells despite the lower efficiency.

Finally, the carbon footprint of DSC modules largely depends on the operational lifetime, but literature registers values between 20 and 120 g CO_2-eq/kWh, which is comparable to crystalline silicon PV modules.

In conclusion, the convenience and environmental impact of each technology will highly depend on the conditions. For the particular case of RecySmart and Single Sensor, it will depend considerably on where is each bin located. In general, DSC modules will give a more balanced energy generation among all bins while conventional panels will have more values in the extremes (from very large to almost no generation) depending on location and position of each bin. Therefore, the same can be expected for the environmental impact associated, having DSC modules installed in the IoT devices or bins similar final carbon footprints than those described in the literature. Nevertheless, and as most LCAs warn, the environmental impact finally depends on various factors that escape the scope of the analysis, and a definite answer is somehow difficult to provide.

4.2.2 Fuel cells

The Spanish project E.LI.GE proposes a new approach for portable fuel cell (similar to the solutions evaluated in the technical assessment) capable of powering devices in the range of 1-100 W (Garraín *et al.*, 2018). The project aims to design and manufacture new electrodes, current collectors, stack planes with favourable technical characteristics to increase power density at the same time of reducing size and weight (58 grams), becoming ideal for portable applications.

An environmental assessment was done to understand the impacts of the manufacturing process of the FC, without considering the hydrogen production (which is quite relevant). As shown in Table 15, the anode is the main contributor to the environmental footprint. This is due to the material used which is PolyEther Ether Ketone (PEEK) and is synthetized in a laboratory, process which consumes much electricity. Then, according to Garraín et al., the environmental impact of the fuel cell highly depends on the materials selected. It is important to mention that as this was a prototype, it might have higher environmental impact as processes are not industrialized and parts should be done with special methods. However, it is a reality that FC for the application studied in this Master thesis are yet not massively deployed so probably will have a lot higher environmental impact that what they could achieve in 5 to 10 years.

Table 15. Environmental impacts of of E.LI.GE FC parts (Garraín et al., 2018)

Impact	Units	Anode	Cathode	Membrane	Metals	Connectors	Total
Climate Change	kg CO_2 eq	2.07E+02	2.67E-01	1.90E-03	1.57E-02	2.82E-02	**2.07E+02**
Ozone Depletion	kg CFC-11 eq	1.51E-05	2.75E-08	8.98E-11	6.35E-10	2.70E-09	**1.51E-05**
Human Toxicity non-cancer	CTU_h	4.12E-05	1.05E-07	8.32E-10	1.33E-08	7.39E-09	**4.13E-05**
Human Toxicity cancer	CTU_h	1.04E-05	6.84E-08	2.93E-10	1.65E-08	1.30E-09	**1.05E-05**
Particle Matter	$PM_{2.5}$ eq	1.64E-01	1.80E-04	6.76E-07	8.12E-06	1.19E-05	**1.64E-01**
Ionising Radiation	kBq U^{235} eq	1.16E+02	7.01E-02	4.49E-04	2.43E-03	6.44E-03	**1.16E+02**
Photochemical Ozone Formation	kg NMVOC eq	8.30E-01	6.39E-04	3.04E-06	5.69E-05	7.68E-05	**8.31E-01**
Acidification	mol_c H^+ eq	2.27E+00	2.18E-03	6.98E-06	6.60E-05	1.29E-04	**2.27E+00**
Terrestrial Euthrophication	mol_c N eq	2.99E+00	2.24E-03	1.00E-05	1.43E-04	2.23E-04	**2.99E+00**
Freshwater Eutrophication	kg P eq	8.84E-02	1.31E-04	7.27E-07	9.22E-06	8.98E-06	**8.85E-02**
Marine Eutrophication	kg N eq	2.89E-01	2.09E-04	1.04E-06	1.38E-05	2.21E-05	**2.89E-01**
Freshwater Ecotoxicity	CTU_e	8.87E+02	3.90E+00	1.77E-02	2.83E-01	1.20E-01	**8.91E+02**
Land Use	kg C deficit	1.87E+02	3.69E-01	1.69E-03	1.95E-02	2.08E-02	**1.87E+02**
Water Resource Depletion	m^3 water eq	1.48E+00	1.15E-03	7.63E-06	4.57E-05	1.70E-04	**1.48E+00**
Mineral, Fossil & Renewable Resource Depletion	kg Sb eq	1.59E-03	4.07E-06	4.17E-08	3.66E-07	2.62E-07	**1.59E-03**

It is worth mentioning the development done by the French company BeFC, which invented a paper-based, ultra-thin, flexible and miniature bioenzymatic fuel cell system. Their technology uses biological catalysts instead of chemical or expensive noble metal catalysts to convert natural substrates such as glucose and oxygen into electricity. The product exploits enzymes, carbon electrodes and paper microfluidics, all of which provide a sustainable and environmentally-friendly method of generating energy. The devices can be operated with just a drop of solution, from tap water to biological fluids to achieve sustainable fuel cells (BeFC, 2021). Moreover, they achieved a very small sized, very suitable for the wearables, IoT devices, and other applications. According to Dr. Jules Hammond, CEO of BeFC, in conversation with the author of this Master thesis, BeFC's power solution can be totally disposable without harming the environment, and could power RecySmart device up to 6 months. He himself stated that it might not be the most environmentally friendly solution due to the needed replacement, but considering that a truck is already passing by the bins with a stated frequency, then the transportation pollution would not be an extra for the replacement of the fuel cell. Nevertheless, this company and its solution is mentioned as a proof that technological advances are allowing for fuel cells to rapidly evolve into more sustainable and adaptable products that can fit more market needs.

The solution received many awards and in March 2021 it was labelled as "Efficient solution" by Solar Impulse Foundation thanks to the remarked environmental benefits listed (Solar Impulse Foundation, 2021):

- 1 m^2 of paper can support the production of 4.000 fuel cells.
- BeFC generates from 1 to 2,5 mW per cm^2.
- 87% less weight. Compared to the mainstream button battery solution CR2032 with a weight of 2.9 g, the solution weighs only 0.4 g.
- No metal and rare materials content.
- Can save 400 lt of water or 1 m^3 of soil from landfill pollution.

4.2.3 Secondary cells

Batteries are always targeted as one of the most contaminant day-to-day waste types. This is mainly due to the presence of heavy metal components that make batteries become hazardous waste once disposed. The most toxic materials in batteries are lead, cadmium and mercury. Then, the reason why batteries are currently so concerning is that they represent the main storage technology for portable power and for the development of renewables, while worsening an environmental burden.

Although advances to reduce the amount of these metals have been achieved by the battery sector, still they are in use. This industry is the largest user of lead in the world. Also, positive steps towards recyclability and second life have been taken, but currently the energy consumed for recovering the materials from a discarded battery is six to ten times higher than that of manufacturing the components out from virgin materials (ReZap, 2017). It is then the large number of cycles what makes secondary batteries more environmental and cost-effective, and there is not much discussion about this among experts.

Regarding lithium-thionyl chloride battery type, there are not many LCAs evaluating the impact of this technology. Thanks to the lack of the most toxic metals and very long duration (thanks for the high energy density and the passivation effect of the battery), its environmental impact is less than that of many other primary cells.

Moreover, moving onto the choice among rechargeable batteries, Matheys et al performed a lifecycle analysis comparing the environmental impact of different rechargeable batteries (Matheys *et al.*, 2009). The evaluation was focused on five different battery technologies used for electric vehicles, but the conclusions are useful for this Master thesis as the types are the same, and the relative results should follow the same pattern regardless of the application (not the absolute).

The study reveals that lead-acid, nickel-cadmium and nickel-metal hydride batteries have similar environmental impact, while lithium-ion and sodium-nickel chloride have less burden. Based on environmental scores, as for the technologies included in the technical assessment it can be said that nickel-cadmium is the most harmful but nickel-metal hydride has almost the same impact (the difference is less than 10%). Then, lithium-ion technology has approximately 50% less impact than the other two technologies. However, the author declare that the results might somehow change, increasing the impact lithium-ion and sodium-nickel chloride if more data (in quantity and accuracy) would be included, for example about the electrolyte.

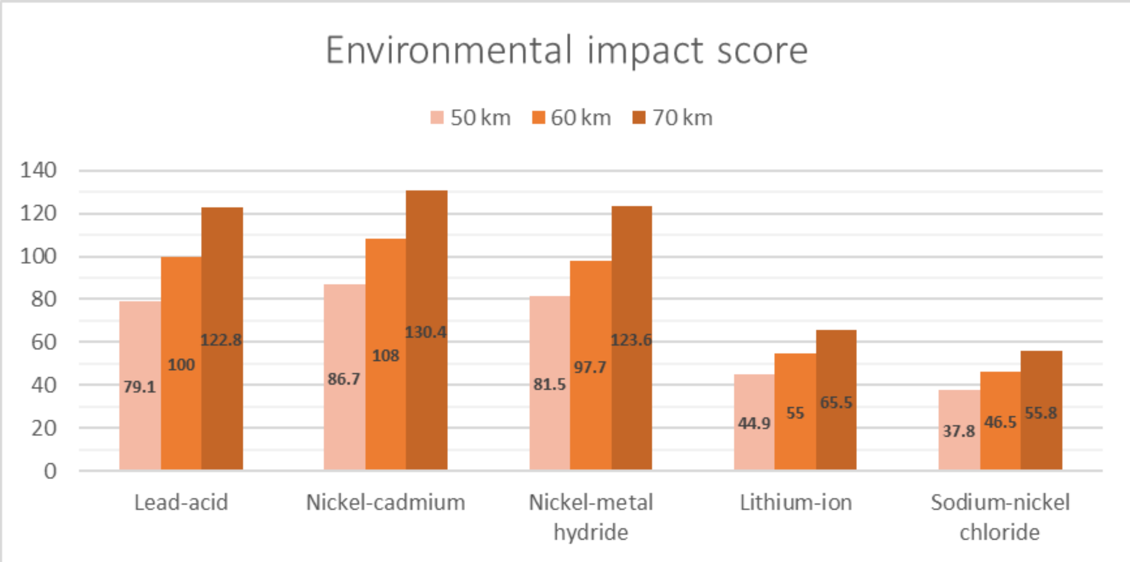


Figure 15. Environmental impacts of different battery types when assuming three different distance ranges for electric vehicles. The 60km range lead-acid battery is the reference, set to 100 (Matheys et al., 2009)

4.2.4 Supercapacitors

The environmental advantages that supercapacitors present against secondary cells are: first, they do not contain lead (vs. lead-acid batteries) or other potentially harmful substances (Chidley, 2015); second, they can be recharged up to 100,000 times so they can last for 10 years.

The European project ENERGY CAPS aimed to introduce the next generation of high-performance, cost-effective and sustainable supercapacitors (CORDIS | European Commision, 2021). The project was financed to design a hybrid supercapacitor for energy efficiency and transport application (EVs specifically). The results report that a process with recycling efficiency of 50% was achieved. However, no info providing carbon footprint and improvement against other supercapacitors or batteries is provided.

Also, the environmental impact of supercapacitors has not been fully assessed in depth. At least, Conte et al. proved that the lead-acid battery system of a forklift would perform better and have less environmental impact if combined with a supercapacitor (Conte *et al.*, 2014). The incorporation of the electrochemical capacitor enhances the duration of the lead-acid battery as the capacity keeps higher after 100 life cycles.

Moreover, Cosutta et. al compared the environmental impact of graphene and activated carbon, two electrode materials for supercapacitors (Cossutta *et al.*, 2020). In overall, they concluded that graphene-based supercapacitor could have up to 2.5 times more GWP than activated carbon-based ones, being the main discrepancy in the production process of both materials. Recyclability can reduce considerably the environmental impact for both technologies.

4.3 ECONOMICAL ASSESSMENT

4.3.1 Current costs

To begin with, the current costs for RecySmart and the Single Sensor will be shown for better understanding of how much would the new added features would represent in the overall cost of the solutions.

Following, the costs for each technology will be assessed. However, an overall economical assessment will be done by the end of the section as some technologies should be assessed together (like PV that needs to be assessed with a storage system).

4.3.1.1 RecySmart

The simplified costs for RecySmart device (with batteries already included) are shown in Table 16 with the 3 lithium-thionyl chloride battery pack cost and weight in the total cost.

Table 16. RecySmart costs (without taxes)

Quantity greater than	***RecySmart*** €/unit	***$LiSOCl_2$ Batteries*** €/pack3	***Batteries cost weight*** %
10	983	20	2.03 %
50	585	20	3.42 %
100	284	20	7.04 %
300	246	20	8.13 %
500	207	20	9.66 %
1.000	188	18	9.57 %
3.000	176	16	9.09 %

4.3.1.2 Single Sensor

The simplified costs for Single Sensor (with batteries already included) are shown in Table 17Table 16 with the 2 lithium-thionyl chloride battery pack cost and weight in the total cost. This are not the real costs, but the price that Recircula Solutions pays to Sensoneo as partner. It can be expected that Sensoneo has a gross margin of 25 to 40%.

Table 17. Single Sensor costs (without taxes)

Quantity greater than	**Single Sensor** €/unit	***$LiSOCl_2$ Batteries*** €/pack2	***Batteries cost weight*** %
0	109	7	6.42 %
50	105	7	6.67 %
100	99	7	7.07 %
300	95	7	7.37 %
500	89	7	7.87 %
1.000	79	7	8.86 %
3.000	75	7	9.33 %

4.3.2 Solar photovoltaic

4.3.2.1 Conventional solar modules

The main cost associated with solar PV is the price itself of the module. Besides, in some cases there might be the need for an adapter. Moreover, most probably some charge controller will be needed. For the costs of PV modules and adapters, Voltaic's quotation will be used (Table

18), as for the extra electronics that might be needed no more than € 5 will be accounted as they are low cost microelectronics.

Table 18. Unitary prices for 1 and 2 W panels, adapter and battery pack (with shipping, without taxes) (Voltaic Systems, 2021)

	1 W Solar panel		2 W Solar panel		Adapter	Battery pack
Scale	P101	P124	P102	P126	A101 Adapter	V25
Retail	€ 17.97	€ 13.24	€ 27.43	€ 17.97	€ 5.68	€ 36.89
10	€ 16.18	€ 11.92	€ 24.69	€ 16.18	€ 0.95	€ 33.20
50	€ 15.89	€ 10.60	€ 21.95	€ 15.85	€ 0.95	€ 28.38
100	€ 15.14	€ 9.93	€ 20.58	€ 15.37	€ 0.95	€ 26.49
500	€ 14.10	€ 8.61	€ 17.83	€ 13.91	€ 0.95	€ 23.18
1,000	€ 13.91	€ 8.04	€ 17.31	€ 13.48	€ 0.95	€ 22.47
5,000	€ 13.43	€ 7.66	€ 16.93	€ 13.01	€ 0.95	€ 20.81

For RecySmart it was recommended that the 2 W option was bought due to the self-consumption of the battery (might not be needed to oversize from 1 to 2 W if use with other battery which is not Voltaic's V25). Checking at model P126, designed to last 5-7 years of outdoor application, it can be seen that the prices are relatively low in comparison with the cost of RecySmart (even less than the current battery pack). For Single Sensor, all quoted panels would be oversized, but taking a look at model P124 it can be expected that a suitable panel could be approximately the same price of the pair of $LiSOCl_2$.

4.3.2.2 Dye-sensitized PV solar cell modules

As for Fujikura's quotation (Table 19), it can be seen that the price of 1 cell (with a purchasing order of 50 units) with rated power 340 µW is € 19.69. This is considerably high taking into account the following:

1) The specific power cost would be 57,941.18 €/W, while for normal PV (taking as reference Voltaic's offer) the cost can be as low as 10.60 €/W. It is clear that the technologies should not be compared equally, as one is intended to generate less but over a wider range of hours and locations. However, the difference is still too much.
2) Considering Fujikura's recommendation that it would be needed 15 pieces for RecySmart device, then it leaves a cost between € 196.35 when pruchasing 2,500 units to € 295.35 when purchasing 50 units, only in dye-sensitized solar cells without considering the storage needed for one single device. In any case, these values are not suitable at all.

Table 19. Fujikura's prices for FDSC-FSC7FGC (with shipping, wihtout taxes) (Fujikura, 2020)

FDSC-FSC7FGC	
Quantity	Unitary price
50	€ 19.69
2,500	€ 13.09
15,000	€ 11.88

For Single Sensor, the recommended cell by Fujikura (no quotation sent) should have a lower price because it has less size and less rated power. Therefore, it can be expected that one cell, enough for covering one sensor, would be around € 15. Although this represents the double of the current battery pair, and still without including the storage device, it still in the range of the acceptable as it would not overpass 10% of the sensor's cost.

4.3.3 Fuel cells

- Currently, all the literature and market highlight fuel cells' high costs as the main challenge for the technology, in contrast to its various advantages. As evaluated during the technical assessment, there seem not be yet fully marketable applications for IoT. Therefore, the studied educational kits will be used as a reference for prices. As an overview, there were two possibilities: one with reversible fuel cells and storage tanks which would work necessarily with PV, and a second one with fuel cells and hydrogen rechargeable cartridges. In Table 20, different kits' costs are shown:
- Kit 1: includes the double reversible FC (FC and electrolyzer) and one storage tank from H-Tec Education. The solar PV should be that of Voltaic, Fujikura, or any other (not included in the costs).
- Kit 2: it is the same as Kit 1 but the reversible FC is the one from Horizon Educational and one storage tank from H-Tec Education.
- Kit 3: it includes a mini PEMFC from Horizon Educational powered by the Hydrostik. Also, it includes the Hydrofill refilling station (the cost is assumed to be divided among 500 units).

From the costs it can be seen that Kit 2 would be more convenient than Kit 1. Then, considering that for Kit 2 the connection with a PV panel would be needed (thus increasing the cost of the total power supply) while Kit 3 can work on its own, they both will be comparable in price.

Table 20. Fuel cells costs for different kits

Fuel cell kits			
Brand	**Item**	**Price**	**Source**
H-Tec Education	Double Reversible FC	€ 85.17	
H-Tec Education	Storage tank 30	€ 17.97	
Kit 1		**€ 103.15**	
Horizon Educational	PEM reversible FC	€ 44.00	
H-Tec Education	Storage tank 30	€ 17.97	
Kit 2		**€ 61.97**	
Horizon Educational	PEM mini FC	€ 39.00	
Horizon Educational	Hydrostik Pro	€ 39.00	
Horizon Educational	Hydrofill Pro (/500)	€ 1.70	
Kit 3		**€ 79.70**	

As for BeFC's fuel cells, there are still no commercial prices available for los volumes. Nevertheless, according to the Solar Impulse Foundation, the financial benefits that could be expected from the scale up of the company for next years would include (Solar Impulse Foundation, 2021):

- Reduction of recycling costs of about 80%.
- Should lead to a 20% cost reduction at full scale production.
- Reduction of prices of some devices up to 60%.

Although it is true that fuel cells are still more expensive than PV or batteries by far, the same that happened with PV over the last decade (price drop even lower than that of fossil fuels) can possibly happen for fuel cells. There is too much expectation in the market for their development thanks to the various challenges they allow to overcome, making them a universal solution to leverage renewable infrastructure and becoming a new leading energy vector (along with electricity, with which they are "interchangeable"). Also, there is a huge amount of public funding being addressed to hydrogen technology. Industries like automotive and energy can impulse the developments in the next 5 to 10 years to accelerate new applications, cost optimization and sustainability for all fuel cell products.

4.3.4 Secondary cells

In the Table 21, costs for NiMH, LiPo and Li-ion batteries are shown. For each chemistry type there are two models, one of which was discussed in the technical assessment and a second one to have another reference price.

Table 21. Costs for different battery types and models (with shipping without taxes)

Secondary cells					
Brand	**Chemistry**	**Size [mm]**	**Voltage [V]**	**Capacity [mAh]**	**Price**
Grepow	NiMH	D - 61xØ31.2	1.2	9,500	€ 12.60
Tenergy	NiMH	D - 61.5xØ33	1.2	10,000	€ 3.46
Grepow	LiPo	Rectangle - 38x24.6	3.7	450-1,000	€ 6.04
EEMB	LiPo	Rectangle - 97x33.5	3.7	3,700	€ 9.27
Voltaic	Li-ion	Square - 77x78	5	6,400	€ 27.81
Vidar	Li-ion	Rectangle - 68x37	3.7	4,400	€ 17.76

The prices for secondary cells are quite competitive, many of them even having lower prices than the current primary cells in use. These prices would be for batteries that were studied for RecySmart device, as they would be too oversized for Single Sensor.

For Single Sensor, it could even be considerable including rechargeable batteries without energy generation. Considering the current pair of batteries that sum up to 5,200 mAh and last between 5 and 7 years, it would not be out of place to consider the same approach but with rechargeable batteries. Taking a look at the prices for NiMH, it could be possible even to have more energy for less price, although the voltage of 1.2 V does not match the current solution. Also, LiPo could be another option. Even if they have less energy density, thinking of recharging them once every 3-4 years is acceptable, or spending up to € 5-10 more than current solution to have the same duration but with rechargeable batteries is also acceptable. It is important to take into account that the disposing of non-rechargeable batteries also represents an extra cost for the waste manager.

4.3.5 Supercapacitors

Supercapacitors have a wide range of specification and prices. Capacitech Cable Based price could not be found, however, there are multiple models of supercapacitors with similar characteristics ranging from less than € 1 up to € 10. Nevertheless, as concluded in the technical assessment, supercapacitors will not be considered as they are an extra to batteries (or FC) but would not be able to cover all the storage by themselves. As the aim of this Master thesis is to propose a first evolution of the power supply, supercapacitors then will be discarded at this stage.

4.3.6 Overall economic assessment

For taking conclusions from an economic perspective, the different alternatives for energy harvesting and storage need to be evaluated. The different combinations to be compared are: 1) Solar PV + secondary cells; 2) DSSC PV + secondary cells; 3) Solar PV + reversible fuel cell + H_2 tank (Only for RecySmart); 4) DSSC PV + reversible fuel cell + H_2 tank (Only for RecySmart); 5) Fuel cells + H_2 cartridge + refilling station; 6) Secondary cells.

The period of analysis will be 5 years and considering purchasing orders for 50 RecySmart or Single Sensors.

4.3.6.1 RecySmart

From Table 22 it can be seen that some technologies should be discarded due to the high cost they represent if applied to RecySmart. These are DSSC PV (either with secondary cells or fuel cells), fuel cells with refillable H_2 cartridges and secondary cells without energy harvesting.

As for the remaining alternatives, solar PV with either secondary cells or reversible fuel cell, the first one looks the most promising because it implies almost half the cost of the current situation. Moreover, although the option with fuel cells looks good in cost, it was already mention that the installation in a waste bin would not be very suitable (for the storage tank) and that the technical feasibility was not guaranteed.

Therefore, from an economic point of view for 5 years, the best alternative is solar PV with secondary cells. Nevertheless, it should be considered that from the client's perspective, this implies a higher CAPEX as almost all the cost is at the beginning. With this option, the initial price of RecySmart is € 36 higher (6,15 % for 50 units). When thought for large deployments, these increase at the beginning can be a difference. For 50 units only (large pilot trial scale), it is € 1,800 which is more than 3 devices. This does not mean that the alternative is not convenient, it is just a fact that is important to have in mind for the company at the moment of selling. First, because margins had not been added yet, and second because usually the battery replacement cost is something that the clients do not have in relevant consideration so it is a cost they do not count too much, making the device look "cheaper", as in Table 16. Of course, both alternatives can be presented to the client with all relevant info to help them make an adequate decision according to their needs.

Table 22. Costs for different technology combinations for RecySmart

RecySmart						
Function	**Technology**	**Unit cost**	**Unit I&M cost**	**Units**	**Cost**	**Description**
Storage	LiSOCl2 primary cells	€ 6.67	€ 0.34	19.25	€ 133.89	Battery pack duration 9.35 months
Current situation: primary cells					**€ 133.89**	
E. Harvester	Solar PV	€ 18.90	€ 4.09	1	€ 22.99	Voltaic's 2W panel + an average price of secondary batteries for 5 days of autonomy min. + extra electronics
Storage	Secondary cell	€ 23.44	€ 0.00	1.52	€ 35.63	
BoS	Extra electronics	€ 10.00	€ 0.00	1	€ 10.00	
Solar PV + secondary cell					**€ 68.62**	
E. Harvester	DSSC PV	€ 19.69	€ 0.27	15	€ 299.44	Fujikura's recommended module (15 cells) + an average price of secondary batteries for 5 days of autonomy min. + extra electronics
Storage	Secondary cell	€ 23.44	€ 0.00	1.52	€ 35.63	
BoS	Extra electronics	€ 10.00	€ 0.00	1	€ 10.00	
DSSC PV + secondary cell					**€ 345.07**	
E. Harvester	Solar PV	€ 18.90	€ 4.09	1	€ 22.99	Voltaic's 2W panel + an average price of FC and storage hydrogen tank + extra electronics
Storage	Reversible FC + H_2 tank	€ 82.56	€ 0.00	1	€ 82.56	
BoS	Extra electronics	€ 10.00	€ 0.00	1	€ 10.00	
Solar PV + reversible FC with H_2 tank					**€ 115.55**	
E. Harvester	DSSC Solar PV	€ 19.69	€ 0.27	15	€ 299.44	Fujikura's recommended module (15 cells) + an average price of FC and storage hydrogen tank + extra electronics
Storage	Reversible FC + H_2 tank	€ 82.56	€ 0.00	1	€ 82.56	
BoS	Extra electronics	€ 10.00	€ 0.00	1	€ 10.00	
DSSC PV + reversible FC with H_2 tank					**€ 392.00**	
E. Generation	Fuel cell	€ 39.00	€ 0.00	1	€ 39.00	Fuel cell and Hydrostik Pro to be refilled with Hydrofill Pro. Each cartridge can be refilled 100 times and each refill will be done every 12 days + extra electronics
Fuel	H_2 cartridge	€ 39.00	€ 0.00	2	€ 78.00	
Refilling	Hydrofill Pro	€ 0.02	€ 1.02	152	€ 158.23	
BoS	Extra electronics	€ 10.00	€ 0.00	1	€ 10.00	
FC + refillable H_2 cartridges					**€ 285.23**	
Storage	Secondary cell pack	€ 59.44	€ 242.92	1.33	€ 321.98	Secondary cell pack: average price of dif. types quant. for 30 days autonomy (in average), hence 59 replacements in 5 years
BoS	Extra electronics	€ 3.00	€ 0.00	1	€ 3.00	
Secondary cells					**€ 324.98**	

4.3.6.2 Single Sensor

From Table 23, the first conclusion is that fuell cells with H_2 cartridges are too expensive, even if from a technical point of view, it could be a suitable solution. The bioenzymatic FCs could be an interesting power solution to evaluate for Single Sensor, but still pricing is not available for low volume purchases.

Then, PV could be an option, either conventional or DSSC. Perhaps, by looking more suppliers for panels and secondary cells, or negotiating prices, or buying larges quantities to have discounts, would help reduce the prices. With solar PV or DSSC PV and secondary cells, the cost increase for Single Sensor is of € 14.66 or € 24.46 respectively. These means increasing the cost in 13% in the best case and more than 25% in the worst. As for filling level sensors there is currently much competition due to the number of suppliers, these increases might be very significant when waste managers choose one solution or the other. Of course, these can be offered as optional additional features.

Moreover, the alternative of only using secondary cells seem quite competitive in price and it would be possible to find a 5 year lasting secondary cell at very low price. With this in the table, even if the combination with PV would have been more competitive in price, it might not be recommendable due to the fact of installing an extra piece of technology into a waste bin. Also, because the advantage of filling level sensors is that in general they are not seen by citizens, hence avoiding vandalism. When adding the solar panel, first it is exposed to stealing, and therefore it gives notices that it might be powering something underneath. In conclusion, it seems that secondary cells alone can be a good and easy change to implement due to the cost competitiveness.

Table 23. Costs for different technology combinations for Single Sensor

Single Sensor						
Function	**Technology**	**Unit cost**	**Unit I&M cost**	**Units**	**Cost**	**Description**
Storage	LiSOCl2 primary cells	€ 3.50	€ 0.00	2.00	€ 7.00	Battery pack duration 6.54 years
Current situation					**€ 7.00**	
E. Harvester	Solar PV	€ 5.20	€ 5.46	1	€ 10.66	Voltaic's 0.3W panel + an average price of secondary batteries for 30 days of autonomy min. + extra electronics
Storage	Secondary cell	€ 4.00	€ 0.00	1	€ 4.00	
BoS	Extra electronics	€ 7.00	€ 0.00	1	€ 7.00	
Solar PV + secondary cell					**€ 21.66**	
E. Harvester	DSSC PV	€ 15.00	€ 5.46	1	€ 20.46	Fujikura's recommended cell + an average price of secondary batteries for 30 days of autonomy min. + extra electronics
Storage	Secondary cell	€ 4.00	€ 0.00	1	€ 4.00	
BoS	Extra electronics	€ 7.00	€ 0.00	1	€ 7.00	
DSSC PV + secondary cell					**€ 31.46**	
E. Generation	Fuel cell	€ 39.00	€ 0.00	1	€ 39.00	Fuel cell and Hydrostik Pro to be refilled with Hydrofill Pro. Each cartridge should be refilled once
Fuel	H_2 cartridge	€ 39.00	€ 0.00	1	€ 39.00	
Refilling	Hydrofill Pro	€ 0.02	€ 2.04	2	€ 4.11	
BoS	Extra electronics	€ 7.00	€ 0.00	1	€ 7.00	
FC + refillable H_2 cartridges					**€ 89.11**	
Storage	Secondary cell pack	€ 10.77	€ 0.00	1	€ 10.77	Secondary cell pack: average price of dif. types quant. for 5 years autonomy. No recharges needed
BoS	Extra electronics	€ 1.00	€ 0.00	1	€ 1.00	
Secondary cells					**€ 11.77**	

5 CONCLUSIONS

5.1 Selected technologies

After the technical, environmental and economical assessment, and evaluating two different IoT devices, one with 335 times the energy consumption than the other, it can be said that for large consumption IoT devices it ends being more convenient to have energy harvesting in place, while for small consumption devices it might be better not to build a complex system but rely only on one energy unit, like secondary cells.

Of course, this will depend totally on the type of application, as for devices with difficult accessibility, even when the consumption is low, some energy harvesting would be recommended. Also, there might be devices that are constantly exposed to a constant energy source. For example, sensors mounted on the electrical grid have a constant electromagnetic field to take profit from with a vibrations energy harvester, or the same for sensors mounted on trains next to the wheels where vibrations can have a fixed frequency.

At the beginning, it was thought that a strategy to cover only the sleep mode would be adequate. However, after all the assessment, it was seen that the active mode represented such a small fraction that the power supply to be selected could cover it or not without it modifying much the results.

For RecySmart device, conventional solar photovoltaics with secondary cells seem a good alternative in all criteria assessed. It is the selected option to proceed to more deep analysis thanks to the following aspects:

1. Technical: it provides a feasible solution that could make the device fully autonomous, at least for South Europe, and stand-alone for 5 years.
2. Environmental: sustainable energy harvesting is provided to the system and the non-rechargeable batteries would be replaced, therefore improving the overall environmental impact of the device. Normal solar PV is less harmful than DSSC modules, and for the secondary cells, Li-ion and LiPo technologies could be the best solutions considering environmental impact.
3. Economical: the proposed combination reduces the overall cost of the device (in 5 years) by almost 10%: It increases the CAPEX but then the OPEX reduction is even greater. Besides, from a market perspective, the technologies are mature and there are multiple suppliers both for PV modules and secondary cells in the market. This provides guarantee of supply plus the possibility to improve costs.

For Single Sensor, the most suitable and easy change would be to replace the current batteries by rechargeable ones, without having an energy harvesting device. This change may imply some modifications in the battery holders and electronics but nothing compared to those needed when an energy harvester is included.

For both devices, it is highly recommended to follow from near the development of all the solutions involving fuel cells as the applications for IoT can become developed in the next years while also the overall costs of the technology can be reduced considerably.

5.2 Suggestions to future work

5.2.1 Solar powered RecySmart

The next steps to advance to the development of Solar powered RecySmart would be the following:

1. Technical:
    a. Balance of system: some modifications would be needed for the electronics of the device, but nothing that would represent a challenge for the technical experts of Recircula Solutions. Efforts should be specially focused in balancing the system: PV, battery, device. Voltages, currents, power input and outputs, and other parameters should be matched among different components, so converters, controllers, chargers and other elements might be needed to incorporate. Also, the cabling and mounting for the PV module should be designed to the application in waste bins, and the proper plugs need to be incorporated in the PCB. The balance of system by part of the HW lead engineer should take about 1 to 3 months.
    b. Solar modules: they must be tested. It would be advisable to buy different models from different suppliers and test 5 to 10 different alternatives. The testing should be long-lasting and in real field. The pilot trial in Sant Cugat, near to our installations, could be the perfect testing field.
    c. Secondary cells: each of the secondary types should be assessed in depth to ensure the compatibility, also with recommendation of our suppliers. Li-ion and LiPo seem to be the best alternative, but even within one chemistry type, multiple brands need to be tested. The problem with batteries is that you buy them from distributors and it is impossible to check the quality a priori. Therefore, testing is needed. It had happened to the technical team that they received partially discharged cells (primary), so particular attention needs to be put in this point.
    d. Energy balance: a deep analysis of how the energy balance would look like for different sites across cities with different shadowing conditions is crucial. In the end, Recircula Solutions needs to guarantee that the device will work. Then, the analysis should also derive in the final sizing and selection of the PV module and battery pack, depending on various factors like average irradiations, minimum irradiations, needed autonomy for the secondary cells, etc.
2. Environmental:
    a. Research: unfortunately, the environmental information of products is not well informed. Therefore, continuous literature research, conversations with suppliers and/or experts, and market research of new developments should be continuously performed. There are new developments that are worth following. One of them is the aluminum-ion secondary cell which is a promising technology mainly because it is remarked as more sustainable that lithium types. Although the environmental assessment showed that lithium batteries can be more sustainable than other chemistries, it does not mean that their production does not have heavy burdens. Mining of lithium presents many complications, while aluminum is a more available resource. Moreover, recycling of aluminium is much more advanced as it is a widely use material.

Another innovation to keep on track are organic and embedded solar cells. Recircula Solutions has applied for a grant along with research centers for the design and production of fully recyclable PCBs and embedded organic solar cells. This organics PV cells can reduce the after-life impact considerably.
Finally, the development of fuel cells for IoT should be followed from very near. Hydrogen technologies are evolving at an unprecedent rate and multiple industries and private and public fundings are pushing the advances to next levels. Companies like BeFC might not take long to launch solutions specially designed for IoT, or the educational kits from Horizon Educational and H-Tec Educational are not far from being applicable to low-power consumption electronics.

3. Economical:
    a. Market research: in this work, only some suppliers were consulted. However, there are multiple suppliers for secondary cells and solar panels. A wider research should be done, and conversations should be held with multiple suppliers to find the best prices. Also, negotiating prices and thinking on buying larger quantities can improve the costs.
    b. Detailed calculations: after the technical team gets involved with the development, some costs that were not considered may come to the surface. After all, there are various estimations along this work as it is a high level overview. When moving forward with the project, there will be more detail in the calculations, both technical and economical.
    c. Financing: current times are beneficial for cleantech companies thanks to the amount of funding being poured in the all the value chains of energy transition and climate change mitigation. For example, ambitious programs like the Green Deal bring financing to the sustainability world. Moreover, after the pandemic, the EU Next Generation Funds are a new opportunity to capture funds for R&D. Therefore, the improvement of RecySmart device towards a more sustainable power supply could be an eligible topic for multiple grants. The development of solar powered RecySmart with normal PV modules might not require too much capital, so the applications for grants could be addressed to more specialized developments in cooperation among multiple entities, as the before mentioned project for recyclable PCBs and organic embedded modules. For example, BeFC and Recircula Solutions could jointly present a project for the development of fuel cells specially designed for IoT.

5.2.2 Energy consumption improvements

Finally, there are some key aspects to improve the power consumption of the device, without regards of the power supply. First, it is acknowledged within the company that the consumptions for both active and sleep mode are quite high and can be improved. The target in the next 6 months for sleep mode in RecySmart device is set to be lower 5 mA (18 mW). The firmware developers are working day by day on reducing this consumption (selection of components in the PCB might change but the biggest gains can be done in optimizing the internal logics of the system). Only, by reducing the sleep mode current from 8 to 5 mA, the overall energy consumption of the device would be decreased by 35%.

Moreover, taking into consideration the function of RecySmart device, which serves a waste characterization system when citizens are recycling, there is no need for the device to be always on or in sleep mode. It can be expected that during certain hours, for example from 00:00 to

06:00, nobody will recycle, or even if they do so, to block the use of the device (they can recycle like always but not through RecySmart device). Then, by reducing the possibility to use RecySmart during 6 hours in the night, an ultra-sleep mode can be achieved. This is common in IoT devices, and the only working system would be an internal timer that by 06:00 will tell the device to shift to sleep mode. Basically, in ultra-sleep mode, the bluetooth and NFC modules would not be waiting for a citizen to come (which is the situation in sleep mode). It would be something similar to how Single Sensor works. With this small modification (assuming 1 mA, though it could be much lower), and considering the current situation with sleep mode at 8 mA, the energy consumption could be reduced by 21%. Finally, if both measures are implemented, the energy consumption can be reduced by 47%. In Table 24, the new situation for RecySmart if the modifications are done is shown.

Table 24. Variables comparison for active, improved sleep, and ultra-sleep modes in RecySmart

RecySmart				
Variable	Units	Active mode	Improved sleep mode	Ultra-sleep mode
Voltage	V	3.6	3.6	3.6
Av. Current	mA	150	5	1
Instant power	mW	540	18	3.6
Time per day	sec	280	64,520	21,600
	%	0.3%	74.7%	25.0%
Energy per day	mWh	42	323	22
	%	10.9%	83.5%	5.6%

Of course, the next steps described in the previous section, and all the assessment, should be reviewed if these modifications are done before the development of new power supply. With such energy consumption reductions, the scenarios might change in favor of other technology combinations.

5.3 Suggestions for other devices

For those looking for a sustainable alternative to power other devices, the recommendation is to follow the same methodology and assess the criterias with the same approach as in this work, but applying the knowledge and conditions relative to that particular device. Of course, the outcome will vary from one device to the other, but it can be ensured that by carefully analysing the different aspects of each technology from high-level perspective, it will be possible to arrive to a well fundamented starting point. The outcomes of applying this methodology will be only the beginning of a deeper technical analysis. Figure 2 and Figure 3 can help understand the steps needed to reproduce this

6 REFERENCES

Akimoto, Y. *et al.* (2020) 'Comparative analysis of fuel cell and battery energy systems for Internet of Things devices', *Energy Reports*, 6, pp. 29–35. doi: 10.1016/j.egyr.2020.08.022.

Alsema, E. A. and De Wild-Scholten, M. J. (2006) 'Environmental Impacts of Crystalline Silicon Photovoltaic Module Production'.

Aman, M. M. *et al.* (2015) 'A review of Safety, Health and Environmental (SHE) issues of solar energy system', *Renewable and Sustainable Energy Reviews*, 41, pp. 1190–1204. doi: 10.1016/J.RSER.2014.08.086.

Asthana, P. and Khanna, G. (2019) 'A broadband piezoelectric energy harvester for IoT based applications', *Microelectronics Journal*, 93, p. 104635. doi: 10.1016/j.mejo.2019.104635.

Battery University (2017) *What's the Best Battery?* Available at: https://batteryuniversity.com/article/whats-the-best-battery (Accessed: 24 October 2021).

Battery University (2021) *BU-209: How does a Supercapacitor Work?* Available at: https://batteryuniversity.com/article/bu-209-how-does-a-supercapacitor-work (Accessed: 24 October 2021).

BeFC (2021) *BeFC® - Bioenzymatic Fuel Cells*. Available at: https://befc.global/ (Accessed: 28 October 2021).

Bogacka, M., Pikoń, K. and Landrat, M. (2017) 'Environmental impact of PV cell waste scenario', *Waste Management*, 70, pp. 198–203. doi: 10.1016/J.WASMAN.2017.09.007.

Cegasa Energía SLU (2018) *Batería Zinc Aire eZ8 | Pilas Industriales Zink Air Alkaline de Cegasa*. Available at: https://www.cegasa.com/ez8 (Accessed: 14 November 2021).

Chidley, A. (2015) *What's Super About Supercapacitors?*, *Avnet Abacus*. Available at: https://www.avnet.com/wps/portal/abacus/resources/article/whats-super-about-supercapacitors/ (Accessed: 29 October 2021).

Choi, J., Jung, I. and Kang, C.-Y. (2018) 'A brief review of sound energy harvesting'. doi: 10.1016/j.nanoen.2018.11.036.

ClimaTemps.com (2021) *Stockholm Climate & Temperatures*. Available at: http://www.stockholm.climatemps.com/ (Accessed: 23 October 2021).

Conte, M. *et al.* (2014) 'Hybrid battery-supercapacitor storage for an electric forklift: A life-cycle cost assessment', *Journal of Applied Electrochemistry*, 44(4), pp. 523–532. doi: 10.1007/s10800-014-0669-z.

CORDIS | European Commision (2021) *Clean and green supercapacitors for energy efficiency and transport applications | ENERGY CAPS Project*. Available at: https://cordis.europa.eu/article/id/148917-clean-and-green-supercapacitors-for-energy-efficiency-and-transport-applications (Accessed: 29 October 2021).

Cossutta, M. *et al.* (2020) 'A comparative life cycle assessment of graphene and activated carbon in a supercapacitor application', *Journal of Cleaner Production*, 242, p. 118468. doi: 10.1016/j.jclepro.2019.118468.

Energiot (2021) *Energiot - Harvesting energy for the Internet of Things*. Available at: http://www.energiot.com/ (Accessed: 3 June 2021).

Engül, H. and Theis, T. L. (2011) 'An environmental impact assessment of quantum dot photovoltaics (QDPV) from raw material acquisition through use', *Journal of Cleaner Production*, 19(1), pp. 21–31. doi: 10.1016/J.JCLEPRO.2010.08.010.

Fletcher, D. D. *et al.* (2012) 'Costs evaluation of introducing a Deposit Refund System in Spain [Evaluación de costes de introducción de un sistema de depósito, devolución y retorno en España]', p. 83.

Fuel Cells Store (2021) *Fuel Cell Store*. Available at: https://www.fuelcellstore.com/ (Accessed: 16 October 2021).

Fujikura (2020) *Fujikura DSSCs (Dye-Sensitized Solar Cells)*. Available at: https://dsc.fujikura.jp/en/?gclid=CjwKCAjwgOGCBhAlEiwA7FUXkthWUUurqjJfVrFvyI5z7rjYQ0lC0GZVq3FqmT_ZeZcvUI1noTNGjBoCjEQQAvD_BwE (Accessed: 10 April 2021).

Garraín, D. *et al.* (2018) 'Life Cycle Assessment of a new portable hydrogen fuel cell : Preliminary streamlined results', (September).

Gillis, A. S. (2021) *What is IoT (Internet of Things) and How Does it Work?* Available at: https://internetofthingsagenda.techtarget.com/definition/Internet-of-Things-IoT (Accessed: 14 November 2021).

Grepow (2021) *Grepow Rechargeable Batteries*. Available at: https://www.grepow.com/ (Accessed: 23 October 2021).

H-Tec Education (2019) 'Operating Instructions R104-Double Reversible Fuel Cell'. Available at: www.myhtec.com (Accessed: 16 October 2021).

Häggström, F. and Delsing, J. (2018) 'IoT Energy Storage - A Forecast', *Energy Harvesting and Systems*, 5(3–4), pp. 43–51. doi: 10.1515/ehs-2018-0010.

Holst, A. (2021) *IoT total revenue worldwide 2019-2030*. Available at: https://www.statista.com/statistics/1194709/iot-revenue-worldwide/ (Accessed: 25 November 2021).

Horizon Educational (2021) *Horizon Educational*. Available at: https://www.horizoneducational.com/horizon-renewable-energy-trainer/p1209 (Accessed: 17 October 2021).

Klugmann-Radziemska, E. and Kuczyńska-Łażewska, A. (2020) 'The use of recycled semiconductor material in crystalline silicon photovoltaic modules production - A life cycle assessment of environmental impacts', *Solar Energy Materials and Solar Cells*, 205, p. 110259. doi: 10.1016/J.SOLMAT.2019.110259.

Maani, T. *et al.* (2020) 'Environmental impacts of recycling crystalline silicon (c-SI) and cadmium telluride (CDTE) solar panels', *Science of The Total Environment*, 735, p. 138827. doi: 10.1016/J.SCITOTENV.2020.138827.

Matheys, J. *et al.* (2009) 'Comparison of the environmental impact of five electric vehicle battery technologies using LCA', *International Journal of Sustainable Manufacturing*, 1(3), pp. 318–329. doi: 10.1504/IJSM.2009.023977.

Motlagh, N. H. *et al.* (2020) 'Internet of things (IoT) and the energy sector', *Energies*, 13(2), pp. 1–27. doi: 10.3390/en13020494.

Murray, J. (2019) *Is the lithium-ion battery having a positive impact on the environment?*, *NS ENergy*. Available at: https://www.nsenergybusiness.com/features/lithium-ion-battery-environmental-impact/# (Accessed: 25 November 2021).

myFC (2021) *Technology*. Available at: https://www.myfc.se/technology (Accessed: 4 September 2021).

myFC Press Office (2017) *myFC shows the world's thinnest fuel cell LAMINA^{TM} Thin Film at Mobile World Congress in Barcelona*. Available at: https://news.cision.com/myfc/r/myfc-shows-the-world-s-thinnest-fuel-cell-lamina--thin-film-at-mobile-world-congress-in-barcelona,c2196407 (Accessed: 14 November 2021).

Nugent, D. and Sovacool, B. K. (2014) 'Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: A critical meta-survey', *Energy Policy*, 65, pp. 229–244. doi: 10.1016/J.ENPOL.2013.10.048.

Odunlade, E. and Granath, E. (2020) 'How to get power supply for IoT devices right'.

ONiO (2020) *Here's why energy-harvesting trumps batteries*. Available at: https://www.onio.com/article/energy-harvesting-trumps-batteries.html (Accessed: 25 November 2021).

Passive Components (2021) *Integrated Cable-Based Flexible Supercapacitors for Energy Harvesting Technologies in IoT*. Available at: https://passive-components.eu/integrated-cable-based-flexible-supercapacitors-for-energy-harvesting-technologies-in-iot/ (Accessed: 6 September 2021).

Pedersen, J. (2021) *Vibrations power tomorrow's IoT devices*, *Force Technology*. Available at: https://forcetechnology.com/en/articles/iot-devices-energy-harvesting-vibrations-energy-powering (Accessed: 20 June 2021).

PowerTech Systems (2021) *The Lithium Difference*. Available at: https://www.powertechsystems.eu/home/tech-corner/lithium-ion-battery-advantages/ (Accessed: 24 October 2021).

Recircula Solutions (2021) *Recircula Solutions - Making smart any waste bin*. Available at: https://recirculasolutions.com/ (Accessed: 14 November 2021).

ReZap (2017) *Batteries and the environment*. Available at: https://rezap.com/batteries-and-the-environment/ (Accessed: 25 October 2021).

Saft Batteries (2020) *Which types of batteries for your IoT devices?* Available at: https://www.saftbatteries.com/energizing-iot/types-batteries-iot-devices (Accessed: 12 April 2021).

Saurav, P. (2018) *Batteries for IoT devices*. Available at: https://www.baseapp.com/iot/batteries-iot-device-types-character/ (Accessed: 23 October 2021).

Sebald, G., Guyomar, D. and Agbossou, A. (2009) 'On thermoelectric and pyroelectric energy harvesting', *Smart Materials and Structures*, 18(12). doi: 10.1088/0964-1726/18/12/125006.

Sinha, S. (2021) 'State of IoT 2021: Number of connected IoT devices growing 9% to 12.3 B', *IoT Analytics*. Available at: https://iot-analytics.com/number-connected-iot-devices/ (Accessed: 25 November 2021).

Solar Impulse Foundation (2021) *Bioenzymatic Fuel Cell* . Available at: https://solarimpulse.com/solutions-explorer/bioenzymatic-fuel-cell (Accessed: 30 October 2021).

State Meteorological Agency -Spanish Government (2021) *Standard climate values. Barcelona Aeropuerto.* Available at: http://www.aemet.es/en/serviciosclimaticos/datosclimatologicos/valoresclimatologicos?l=0076&k=cat (Accessed: 23 October 2021).

Tawalbeh, M. *et al.* (2021) 'Environmental impacts of solar photovoltaic systems: A critical review of recent progress and future outlook', *Science of the Total Environment*, 759. doi: 10.1016/j.scitotenv.2020.143528.

Tsoutsos, T., Frantzeskaki, N. and Gekas, V. (2005) 'Environmental impacts from the solar energy technologies', *Energy Policy*, 33(3), pp. 289–296. doi: 10.1016/S0301-4215(03)00241-6.

Valoriza Medioambiente (2021) *Battery-Less Sensor: a sustainable approach to the Internet of Things*. Available at: https://www.sacyr.com/en/-/battery-less-sensor (Accessed: 25 November 2021).

Veerubhotla, R., Nag, S. and Das, D. (2019) 'Internet of Things temperature sensor powered by bacterial fuel cells on paper', *Journal of Power Sources*, 438. doi: 10.1016/j.jpowsour.2019.226947.

Veltkamp, A. C. (2007) 'Environmental life cycle analysis of large area dye sensitized solar modules; status and outlook', *Presented at: 22nd European Photovoltaic Solar Energy Conference and Exhibition*, 3(September), pp. 3–7. Available at: http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Environmental+life+cycle+analysis+of+dye+sensitized+solar+devices;+status+and+outlook#0.

Voltaic Systems (2021) *Solar for IoT and Remote Sensors*. Available at: https://voltaicsystems.com/iot/#faq_1 (Accessed: 16 October 2021).

Weather Spark (2021) *Compare the Climate and Weather in Barcelona and Chiba - Weather Spark*. Available at: https://weatherspark.com/compare/y/47213~144000/Comparison-of-the-Average-Weather-in-Barcelona-and-Chiba (Accessed: 21 October 2021).

de Wolff, D. (2021) 'The future of the IoT (batteries not required)', *MIT News*. Available at: https://news.mit.edu/2021/future-iot-batteries-not-required-0521 (Accessed: 25 November 2021).

Worthman, E. (2020) *Fuel Cells Vital to Powering IoT*, *AGL Magazine*. Available at: https://www.aglmediagroup.com/fuel-cells-vital-to-powering-iot/ (Accessed: 4 September 2021).

XFC (2019) *Portable fuelcell*, *Portable fuelcell*. Available at: https://www.xfc.co.kr/portable-fuelcell/ (Accessed: 4 September 2021).