Introduction and problem definition
Lithium-ion batteries in the Off-Grid Solar sector
Battery procurement and challenges for the Off-Grid Solar sector
Options for end-of-life management of lithium-ion batteries
Call for action for the Off-Grid Solar sector
This white paper aims to supply decision making in the sector with a clearer understanding about the most significant issues at play when it comes to lithium-ion batteries and their recycling process. In this document we address the current lithium-ion technologies, market drivers and their impact on the OGS sector. Additionally, we discuss the state-of-art lithium-ion recycling technology and how the OGS sector can improve end-of-life management, for pico-solar and solar home systems (SHS).

The OGS sector in Africa is growing rapidly thanks to falling costs, combined with improvements in the energy efficiency of end-use technologies. A new World Bank Group and GOGLA report published in March 2020 shows that the off-grid solar industry has grown into a $1.7 billion annual market providing lighting and other energy services to 2020 million users in Africa. Moreover, the OGS sector is instrumental for the achievement of the Sustainability Development Goals (SDG), which aim to provide universal access to modern energy and increase global percentage of renewable energy.

Improvements in efficiency and costs of OGS systems have been continuously achieved due to technological advancements of batteries, which are the most expensive component of a OGS device. OGS devices commonly use both lithium-ion and lead-acid batteries. Lead-acid batteries are cheaper to maintain, cost effective and have a longer lifespan, lower self-heating rates, as well as higher capacity (NiMH) and lead-acid, lithium-ion have lower environmental impacts, in comparison with other battery types, such as nickel metal hydride (NiMH) and lead-acid. Lithium-ion batteries have lower environmental impacts, a longer lifespan, lower self-heating rates, as well as higher capacity and power6.

These technical advances make it a key energy for energy storage technologies and a number of other applications such as electric mobility applications, portable consumer electronics and power tools. Despite the benefits and market success of lithium-ion to date, there is an increasing concern with the end-of-life management of lithium-based batteries, in terms of particularly the environment and public health risks associated with the disposal of obsolete lithium-ion batteries. Facilities for the recycling of lithium-ion are not available in Africa and as the market demand increases so does the potential impact on supply chains and end-of-life management. This impact will need to be assessed from a life-cycle perspective.

In terms of performance, today’s lithium-ion batteries can achieve energy densities up to 300 Wh/kg7: this high energy density means a significant amount of energy packed into the same volume. The off-grid solar sector has grown enormously over the past 10 years. From just $0.2 billion in 2010, annual revenue grew rapidly at 20%, while sales volumes grew at 40% per annum.8 These technical advantages make it a key energy for energy storage technologies and a number of other applications such as electric mobility applications, portable consumer electronics and power tools. The off-grid solar sector has grown enormously over the past 10 years. From just $0.2 billion in 2010, annual revenue grew rapidly at 20%, while sales volumes grew at 40% per annum.9


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Figure 2 explains the key parameters that procurement teams look for when deciding which lithium-ion battery to pick (capacity, power, lifespan, cost, performance and safety).

The six types of battery available are lithium nickel manganese cobalt (NMC), lithium titanate (LTO), lithium iron phosphate (LFP), lithium cobalt oxide (LiCoO2), lithium manganese oxide (LMO) and lithium nickel cobalt aluminium oxide (NCA).

For the OGS sector, the two most important parameters are:
1. Safety – Temperature will be higher in Sub-Saharan Africa compared to Western countries, meaning that the chemistry used needs to be resilient at higher temperatures.
2. Cycle life – Pico solar typically has a lifespan of 1-3 years and SHS can last 6-10 years.

As the device is deployed in remote areas, failure within the warranty period can be very costly for the OGS company, especially as repair and maintenance is challenging logistically.

These two key parameters mean that most OGS companies chose LFP for solar home appliances, as they have a long service life and a deep-cycling ability that make it suitable for stand-alone applications.

The LFP battery also has a high current rating and good thermal stability. These attributes make it fit for use in numerous OGS systems, whether powering a fridge, TV, fan or a water pump.

LFP has one major drawback - it has poor material recovery capabilities, which means it is a challenge to recycle.

Pico solar applications, being much smaller than SHS, tend to use LCO batteries, as they have high energy density, so are lightweight for use in consumer electronics such as smartphones, lights and torches. However, it has a comparatively short life span and low thermal stability, making them unsuitable for most other applications.

Naturally, other chemistries also exist, and new variations are arriving on the global battery market such as sodium ion batteries but the lack of availability and the high price of new technologies are slowing their adoption.

The off-grid sector is therefore unlikely to be the first adopter of such new technologies. Instead, the sector has to wait for other sectors to scale up production and consumption before OGS can reap the benefits of economies of scale.
3.1 EV’s Leading the Charge

The automotive sector is predicted to be the main force behind lithium-ion production. By 2030, it is estimated that electric vehicles (EVs) are expected to be deployed on roads worldwide. This growth is driving the cost of lithium-ions down through improved technology and ramped-up production volume.

As of 2019, Morgan Stanley, a financial consultancy, announced that battery pack prices have already fallen to $150/kWh and Tesla is expected to reach the $100/kWh milestone by 2022. This milestone represents the tipping point where EVs become commercially competitive with internal combustion engine powered vehicles. However, only large-scale EV manufacturers are able to source lithium-ion at such competitive prices as they have high manufacturing optimisation and economies of scale.

By contrast, the off-grid sector, with its significantly lower demand, is not benefitting from the same level of low purchase price.

3.2 Global Battery Producers

While there is a plethora of lithium-ion suppliers, by and large, they can be divided into three tiers (Figure 1) arranged by reputation for quality and volume. It is predicted that there will be a shortage of Tier 1 batteries for developed country EV manufacturers, while Tier 2 and Tier 3 batteries are not yet capable for EV application.

Consequently, it stands that the off-grid sector will keep sourcing batteries mostly from Tier 3 battery suppliers. Tier 3 manufacturers are predominantly found in China and encompasses many operators. They tend to appear homogeneous in terms of offering and price, however they vary widely in performance.

The main challenge for the OGS operators is how to choose the right battery at an affordable price tag that will help them deliver a reliable service to their customers, in line with their product specifications.

Figure 3: Major lithium-ion cell suppliers by quality and volume taken from Benchmark Minerals’ Lithium Ion Battery Megafactory Assessment, February 2019

3.3 Financial Stability of Battery Suppliers

A study produced by the Grantham Institute and Shell Foundation shone light on the significant differences between performance (lifetime and degradation) of batteries manufactured by different suppliers reported by off-grid energy companies. It also highlighted that a key decision criterion for mini-grid and solar home-system providers is the financial stability of the battery suppliers – as many off-grid companies have seen their initial battery supplier face bankruptcy.

Chinese battery suppliers have benefitted from government support from NEV subsidies (New Energy Vehicle – a term commonly used in the Chinese context for electric and other alternative drivetrain vehicles) but it has come with consequences. The scheme introduced in 2015 offered subsidies for Chinese EVs produced using government recommended lithium-ion suppliers. This list excluded foreign firms and contributed to the growth of China’s battery sector.

Nonetheless, in 2019 with the industry maturing, China scrapped the recommendations list of suppliers, allowing foreign lithium-ion manufacturers to enter the Chinese market. This left many Tier 3 suppliers struggling with the new competition and filing for bankruptcy.

Consequently, the OGS faces further procurement challenges as it does not have access to well-established battery manufacturers.
The energy access crisis in Sub-Saharan Africa has been greatly improved by OGS but the sector is at risk of undermining its achievements because of the environmental challenge in the region. Recent news has highlighted the waste management challenges for both the environment and public health in developing countries.

Electric and electronic products (including refillable solar products) are being disposed of inappropriately, with lead-acid and lithium-ion batteries being found in landfills around the world. Despite the absence of legal obligations, many companies in the sector are keen to address these issues, either through the establishment and trial of collection and the take-back of used products. Much work is still underway to create standards for collection and disposal of used lithium-ion from the market. The lack of recycling infrastructure currently available in Africa is a key hurdle to overcome here, as with the implementation of a waste regulation framework.

To understand how battery regulation can be developed effectively, the European Union Battery Directive should be used as a prime example. The European Union Battery Directive (2006/66/EC) entered into force in 2008 and is transposed in national law by each Member State. In addition to imposing requirements on producers to increase the take-back and recycling, irrespective the economic feasibility of the process itself, it also gives sufficient leeway to increase recycling efficiency. All collected and identifiable spent batteries must be treated and recycled in order to recover their components.

For lithium-ion, a recycling efficiency of at least 50% by weight must be achieved. Since 2006, the Directive has been revised several times, most recently in 2013. The Battery Directive is currently under major revision, and the presentation of a draft version of the new Directive was published in December 2020 and includes:

• Increased collection targets for consumer batteries
• The introduction of element-specific recycling quotas for Li, Co, and Ni.
• More specific definitions for ‘recycling’, ‘reuse’, ‘treatment’, and ‘disposal’
• Uniform regulations for the calculation of recycling quotas

In all European Economic Area Countries, producers are currently held financially responsible for waste battery collection schemes. The organizational responsibility for the schemes and the responsibility for financing and managing the battery operations to fund varies between member states.

In a growing number of African and Asian countries, dedicated legislation is being passed to address the issue of used batteries, and to ensure that all products taken to market have a recycling end of life. This means that the pro-collaboration will soon be financially responsible to ensure proper collection and recycling processes.

4.2 Recycling Technologies for Lithium Batteries

4.2.1 Material Supply

The focus of the lithium-ion recycling processes is driven by market concentration of lithium, cobalt and graphite and supply limitations. The toxicity, environmental risk, and sustainability considerations vary between member states.

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The challenge here is getting the OGS sector access to this type of information. As mentioned in Chapter 3, OGS companies struggle to compete with traditional electronics producers because of their knowledge. As a result, the OGS sector will continue to face difficulty unless it has low-quality scrap with uncorrectable material properties.

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4.2.3 Recycling Processes

Lithium-ion end-of-life management after collection of spent batteries typically comprises pre-processing, hydrometallurgical and pyrometallurgical recycling steps. In the next section, we will introduce the different recycling methods for lithium-ion batteries, resources, separation, and recovery. This section aims to provide the necessary background to understand the next sections.

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4.2.4 Global Capacity for Recycling

Major capacity for the recycling of batteries in general, and more specifically lithium-ions, exist in Europe, North America, Japan, and China as illustrated in Table 2 and Figure 4. No industrial-scale recycling of lithium-ion batteries has been reported to take place in Africa.

Instead, spent batteries are either landfilled or collected and sent to facilities in Europe for material recycling, when economically viable.

Figure 4: Global capacity for the recycling of spent Li-Ion batteries (Mayyas et al. 2019)

<table>
<thead>
<tr>
<th>Technology</th>
<th>Pyrometallurgy</th>
<th>Hydrometallurgy</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Recovered materials</strong></td>
<td>Ni, Co, Cu</td>
<td>Ni, Co, Cu, Mn, Li, P, Al</td>
</tr>
</tbody>
</table>
| **Advantages of the process** | - Process is operating commercially  
- Able to deal with high volumes  
- Great tolerance for material composition while melting  
- Lower operational cost (compared to hydrometallurgy)  
- For Li-ion: High yield for cobalt, nickel and copper (even if input composition varies without exceeding cost)  
- No sorting or size reduction  
- Profit from recovery of Co, Ni, Cu | - Economical on a smaller scale  
- Operate at low temperature, low energy  
- Does not require large investment  
- Theoretically possible to recover all metals in Li-Ion batteries  
- Output products are of high purity/quality  
- Output products are directly usable for manufacturing industry  
- No generation of off-gas (but instead wastewater)  
- Can be used for the mix of cathodes |
| **Disadvantages of the process** | - Requires charge to accept material with reduced cobalt content  
- Metals with high oxygen affinity (such as Li, Mn, Al) are irreversibly lost in the slag  
- Indispensable off-gas cleaning and off-gas monitoring of remaining organic, fluoride and heavy metal nano-powders  
- Large capital expenditure is necessary for an economical industrial-scale smelting plant (high all cost due to gas treatment and processing needed to separate metals)  
- Not useful for LFP | - Low variety in input composition required  
- Minor changes of input materials  
- Minor changes in the reactions and significant decline of metal recovery efficiency  
- Wastewater treatment needed  
- Expected high cost due to large consumption of chemicals  
- Additional processing needed to separate metals  
- Not useful for LFP |

Table 1: Comparative study of lithium-ion recycling processes (based on Accurec, 2015)²⁴

²⁴ Accurec 2015: Comparative Study on Li-ion Battery Recycling Technologies, CloseWEEE unpublished report
In the current context, there is a consensus around the key elements involved in the battery market and the off-grid solar sector when considering lithium-ion battery recycling. The supply chain is complex, with a growing demand for batteries and the off-grid solar sector. The challenge is to manage the growing volume of waste batteries in a way that is sustainable and environmentally friendly.

### Call for Action for the Off-Grid Solar Sector

1. **Sustainability of Supply**
   - To ensure proper collection and handling of batteries.
2. **End-of-Life Management**
   - To ensure proper collection and handling of batteries.
3. **Resource Management**
   - To ensure proper collection and handling of batteries.
4. **Local Infrastructure needs to be established**
   - To ensure proper collection and handling of batteries.


<table>
<thead>
<tr>
<th>Company (HQ location)</th>
<th>Recycling Facility locations</th>
<th>Battery types</th>
<th>Process</th>
<th>Recycling volume, tons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hi-Tech Co. (GEM) (CN)</td>
<td>Ningxiang, Changsha, Hunan</td>
<td>NiMH, Li-ion</td>
<td>Hydrometallurgical</td>
<td>20.000-30.000</td>
</tr>
<tr>
<td>Shenzhen Green Eco-manufacturer (CN)</td>
<td>Jingmen, Hubei (CN)</td>
<td>Li-ion, NiMH</td>
<td>Pyrometallurgical</td>
<td>7.000</td>
</tr>
<tr>
<td>Hunan BRUNP (CN)</td>
<td></td>
<td></td>
<td>Mechanical</td>
<td>1.000-3.000</td>
</tr>
<tr>
<td>Nippon Recycle Center Corp. (JP)</td>
<td>Miyagi (JP)</td>
<td>NiCd, NiMH, Li-ion, alkaline</td>
<td>Pyrometallurgical</td>
<td>n/a</td>
</tr>
<tr>
<td>Metals and Mining Co. (JP)</td>
<td></td>
<td></td>
<td>Mechanical</td>
<td>n/a</td>
</tr>
<tr>
<td>Dowa Eco-System Co. Ltd. (JP)</td>
<td>Richmond, VA (US)</td>
<td>Li metal, Li-ion</td>
<td>Hydrometallurgical</td>
<td>4.500</td>
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<tr>
<td>AERC Recycling Solutions (US)</td>
<td>Allentown, PA (US)</td>
<td></td>
<td>Mechanical</td>
<td>n/a</td>
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<td>G&amp;P Batteries (UK)</td>
<td>Darlaston (UK)</td>
<td>Various including Li-ion</td>
<td>Mechanical</td>
<td>120-150</td>
</tr>
<tr>
<td>AEA Technology (UK)</td>
<td>Sutherland (UK)</td>
<td>Li-ion</td>
<td>Mechanical</td>
<td>1.000</td>
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<td>Recupyl S.A. (FR)</td>
<td>Grenoble (Fr)</td>
<td>Li-ion</td>
<td>Hydrometallurgical</td>
<td>110</td>
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<tr>
<td>Euro Dieuze / SARP (FR)</td>
<td>Dieuze</td>
<td>Li-ion</td>
<td>Hydrometallurgical</td>
<td>200</td>
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<tr>
<td>Batrec Industrie AG (CH)</td>
<td>Wimmis (CH)</td>
<td>Li</td>
<td>Pyrometallurgical with mechanical treatment of the slag to extract Co and Ni</td>
<td>300</td>
</tr>
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<td>SNAM (FR)</td>
<td>Saint Quentin Fallavier (FR)</td>
<td>NiCd, NiMH, Li-ion</td>
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### Options for end-of-life management of lithium-ion batteries

- **A. Ensure proper channelling of lithium-ion to current recycling infrastructure, which goes hand-in-hand with the need of a financing mechanism**, given the high cost of lithium-ion battery recycling or the off-grid solar sector. Recycling is always the best option after refurbishment or repurposing loops have been explored.
- **B. Develop local recycling infrastructure.** In most cases for the off-grid sector, they adopt pyrometallurgical processes, as hydrometallurgical processes have limits to volumes and economics of scale. Integrating the two approaches could also be beneficial and development of such processes would partially mitigate the economic costs associated with transboundary shipment of waste.
- **C. Develop safe interim/temporary storage of lithium-ion batteries** for LFP in particular. This is needed to allow time for demand to grow and for companies to develop interest in recovering the active material of electrodes through in-stream treatment of LFP waste.
- **D. Dispose of the batteries, if environmentally sound landfills are available, landfilling in regions where the local authority has no legal obligation to ensure proper collection and treatment.** Whether it is a government subsidy programme, a private sector donor or an NGO, contracts and tenders need to go further than simply asking partners to state whether they have an end-of-life policy but should also ensure the end-of-life financing is planned since the early stage.

### Table 2: Summary of lithium-ion recycling processes and capacities (based on Velázquez-Martínez et al. 2019, Lebedeva et al. 2016, Accurec, 2015)

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<td>Nippon Recycle Center Corp. (JP)</td>
<td>Miyagi (JP)</td>
<td>NiCd, NiMH, Li-ion, alkaline</td>
<td>Pyrometallurgical</td>
<td>n/a</td>
</tr>
<tr>
<td>Metals and Mining Co. (JP)</td>
<td>Richmond, VA (US)</td>
<td>Li metal, Li-ion</td>
<td>Hydrometallurgical</td>
<td>4.500</td>
</tr>
<tr>
<td>Dowa Eco-System Co. Ltd. (JP)</td>
<td>Allentown, PA (US)</td>
<td>Various including Li-ion</td>
<td>Mechanical</td>
<td>n/a</td>
</tr>
<tr>
<td>AERC Recycling Solutions (US)</td>
<td>Darlaston (UK)</td>
<td>Various including Li-ion</td>
<td>Mechanical</td>
<td>120-150</td>
</tr>
<tr>
<td>G&amp;P Batteries (UK)</td>
<td>Sutherland (UK)</td>
<td>Li-ion</td>
<td>Mechanical</td>
<td>1.000</td>
</tr>
<tr>
<td>AEA Technology (UK)</td>
<td>Saint Quentin Fallavier (FR)</td>
<td>NiCd, NiMH, Li-ion</td>
<td>Hydrometallurgical</td>
<td>1.500-2.000</td>
</tr>
<tr>
<td>Recupyl S.A. (FR)</td>
<td>Grenoble (Fr)</td>
<td>Li-ion</td>
<td>Hydrometallurgical</td>
<td>110</td>
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<tr>
<td>Euro Dieuze / SARP (FR)</td>
<td>Dieuze</td>
<td>Li-ion</td>
<td>Hydrometallurgical</td>
<td>200</td>
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<tr>
<td>Batrec Industrie AG (CH)</td>
<td>Wimmis (CH)</td>
<td>Li</td>
<td>Pyrometallurgical with mechanical treatment of the slag to extract Co and Ni</td>
<td>300</td>
</tr>
<tr>
<td>SNAM (FR)</td>
<td>Saint Quentin Fallavier (FR)</td>
<td>NiCd, NiMH, Li-ion</td>
<td>Hydrometallurgical</td>
<td>1.500-2.000</td>
</tr>
<tr>
<td>Accurec Recycling GmbH (DE)</td>
<td>Mülheim (DE), Krefeld (DE)</td>
<td>NiCd, NiMH, Li-ion</td>
<td>Pyrometallurgical with H treatment of the slag</td>
<td>30</td>
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<tr>
<td>Glencore</td>
<td>Nivala (FI)</td>
<td>NiCd, NiMH, Li-ion</td>
<td>Pyrometallurgical</td>
<td>n/a</td>
</tr>
<tr>
<td>Umicore Battery Recycling (BE)</td>
<td>Commentry (FR)</td>
<td>Li-ion</td>
<td>Pyrometallurgical</td>
<td>120-150</td>
</tr>
<tr>
<td>Valdi (ERMET) (FR)</td>
<td>Commentry (FR)</td>
<td>Various including Li-ion</td>
<td>Pyrometallurgical</td>
<td>1.000-1.500-2.000</td>
</tr>
<tr>
<td>Retriev Company (HQ location)</td>
<td></td>
<td></td>
<td>Mechanical</td>
<td>n/a</td>
</tr>
</tbody>
</table>

### Call for action for the Off-Grid Solar sector

1. **Sustainability of Supply**
   - To ensure proper collection and handling of batteries.
2. **End-of-Life Management**
   - To ensure proper collection and handling of batteries.
3. **Resource Management**
   - To ensure proper collection and handling of batteries.
4. **Local Infrastructure needs to be established**
   - To ensure proper collection and handling of batteries.