LITHIUM-BASED BATTERIES & THE OFF-GRID SOLAR SECTOR

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Authors
Federico Magalini
Alexander Clarke
Harini Hewa Dewage
Gergana Dimitrova
Christian Clemm
Franziska Maisel

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INTRODUCTION AND PROBLEM DEFINITION

This white paper aims to supply donors working in the sector with a clearer understanding about the most significant issues at play when it comes to batteries in off-grid solar (OGS) sector.
In this document we address the current lithium-ion technologies, market drivers and their relevance to the OGS sector. Additionally, we will 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[1] published in March 2020 shows that the off-grid solar industry has grown into a $1.75 billion annual market providing lighting and other energy services to 420 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 an OGS device.
OGS devices commonly use both lithium-ion and lead-acid batteries. Historically, lead-acid batteries, owing to their wide availability, robustness and cost-effectiveness were the preferred energy storage solution.
In recent years, development of lithium-ion battery technologies, falling prices and increased availability have resulted in a switch from lead-acid to lithium-ion, as they are more efficient at storing power per unit mass and have a longer lifecycle compared to the older lead-acid technology.

Rechargeable lithium-ion's are indispensable for the transition towards low-carbon mobility and decarbonised energy generation.
In terms of performance, today's lithium-ion batteries can achieve energy densities up to 300 Wh/kg[2]: this high energy density means increasing the amount of energy packed into the same volume[3].
In comparison with other battery types, such as nickel metal hydride (NiMH) and lead-acid, lithium-ion have lower environmental impacts, a longer lifespan, lower self-heating rates, as well as higher capacity and power[4].
These technical advantages make it a key enabler for energy access 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 inappropriate 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.

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[1] https://www.lightingglobal.org/wp-content/uploads/2020/03/VIVID%20OCA_2020_Off_Grid_Solar_Market_Trends_Report_Full_High.pdf
[2] Durmus, Y. E., Zhang, H., Baakes, F., Desmaizieres, G., Hayun, H., Yang, L., Kolek, M., Küpers, V., Janek, J., Mandler, D., Passerini, S., Ein-Eli, Y., Side by Side Battery Technologies with Lithium-Ion Based Batteries. Adv. Energy Mater. 2020, 10, 2000089. https://doi.org/10.1002/aenm.202000089
[3] Rahimzei et al., 2015: Ehsan Rahimzei, Kerstin Sann, Dr. Moritz Vogel, Kompendium: Li-Ionen-Batterien
[4] Velázquez-Martínez; Valio; Santasalo-Aarnio; Reuter; Serna-Guerrero (2019): A Critical Review of Lithium-Ion Battery Recycling Processes from a Circular Economy Perspective. In: Batteries 5 (4), S. 68. DOI: 10.3390/batteries5040068.

2

LITHIUM-ION BATTERIES IN THE OFF-GRID SOLAR SECTOR

The off-grid solar sector has grown enormously over the past 10 years.
From 2017 to 2019, annual revenues grew rapidly at 30%, while sales volumes grew at 10% per annum.[5]
The sector has a heavy reliance on batteries as virtually every product sold needs to store the electricity generated overnight in remote locations.
Battery storage capacity typically ranges from 9 Wh for a small pico photovoltaic (PV) system to over 1 MWh for large mini-grids, depending on the size of the off-grid installation.

Understanding what battery type to choose is not as simple as it used to be.
For the off-grid sector, the options are largely boiled down to either lead-acid or lithium-ion but there are now numerous different lithium-ion batteries with variations in their chemical composition, mainly with regard to the anode and cathode materials as well as separator and electrolyte composition.

Each lithium-ion type has its own characteristics, meaning that the different types of Li-ion battery are used in different applications, as outlined in Figure 1.

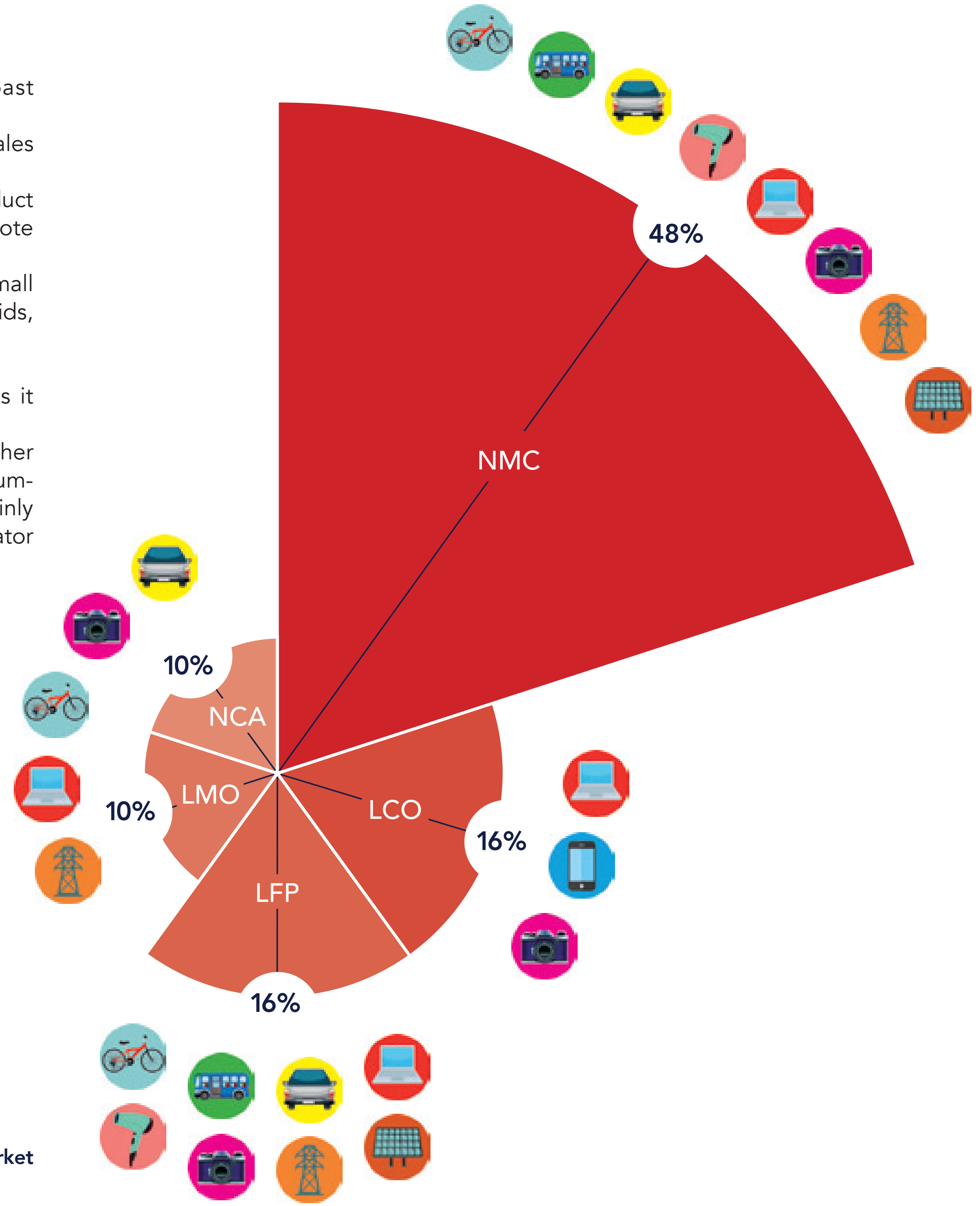

Figure 1: the five main lithium-ion chemistries, their application and market share (adapted from Yole 2017 and Lebedeva et al., 2016).

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[5] https://www.lightingglobal.org/wp-content/uploads/2020/03/VIVID%20OCA_2020_Off_Grid_Solar_Market_Trends_Report_Full_High.pdf

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 (LiCoO^2), lithium manganese oxide (LMO) and lithium nickel cobalt aluminium oxide (NCA).

Figure 2 Comparison of characteristics of common lithium-ion types[6].

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 2-3 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[7].

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.

[6] taken from Miao, Yu & Hynan, Patrick & von Jouanne, Annette & Yokochi, Alexandre. (2019). Current Li-Ion Battery Technologies in Electric Vehicles and Opportunities for Advancements. Energies. 12. 1074-1094. 10.3390/en12061074
[7] Battery university, 2020: https://batteryuniversity.com/learn/article/types_of_lithium_ion

3.1 EV's Leading the Charge

The automotive sector is predicted to be the main force behind lithium-ion production.

By 2030, 125 million electric vehicles (EVs) are expected to be deployed on roads worldwide[8].

This growth is driving the cost of lithium-ions down through improved technology and ramped-up production volume.

In 2019, Bloomberg New Energy Finance announced that battery pack prices have already fallen to $156/kWh and Tesla is expected to reach the $100/kWh milepost by 2023[9].

This milepost represents the tipping point when EVs become commercially competitive against internal combustion engine powered vehicles. However, only large scale EV manufacturers are able to source lithium-ions 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 countries' EV manufacturers, while Tier 2 and Tier 3 batteries are not yet capable for EV application.

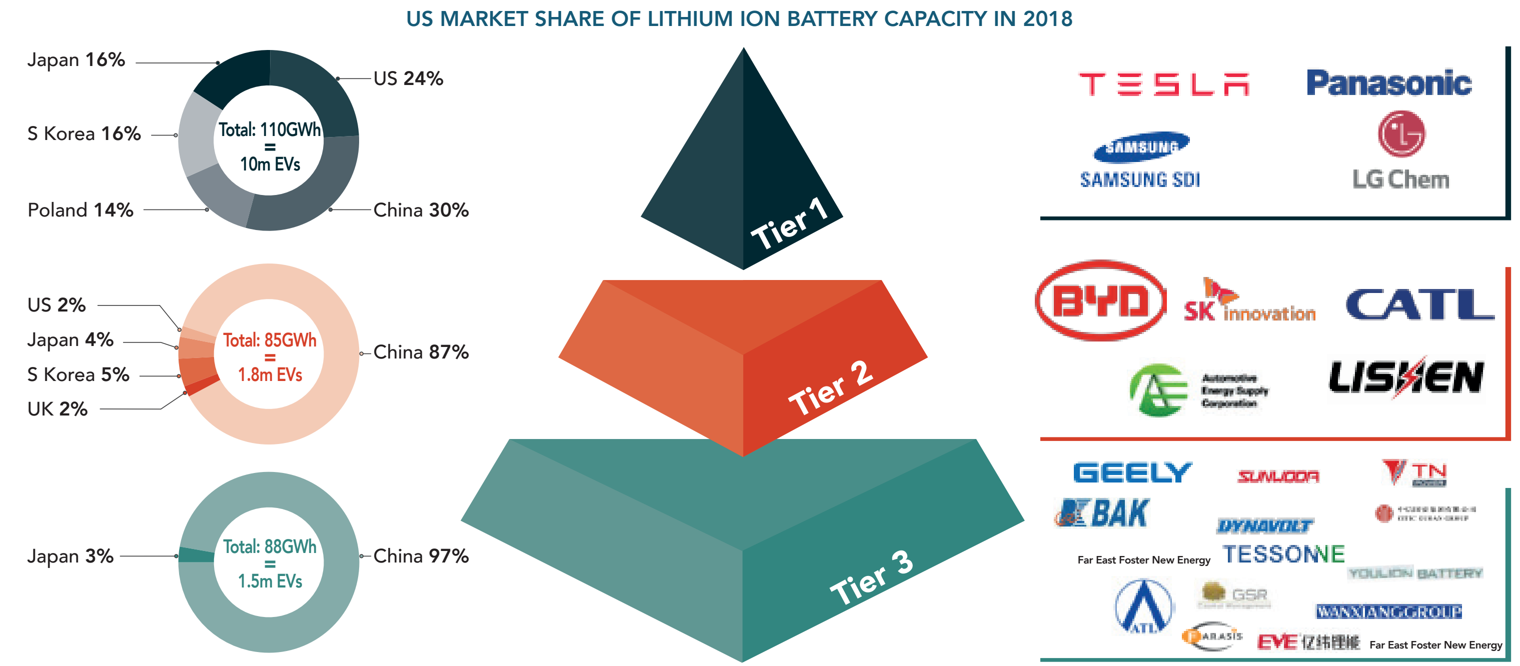
Consequently, it is likely that the off-grid sector will keep sourcing its batteries mostly from Tier 3 battery suppliers.

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 with 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



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[8] IEA, Global Electric Vehicle Outlook 2018 Report

[9] https://about.bnef.com/blog/battery-pack-prices-fall-as-market-ramps-up-with-market-average-at-156-kwh-in-2019/

3.3 Financial Stability of Battery Suppliers

A study produced by the Grantham Institute and Shell Foundation[10] 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 emphasised 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.

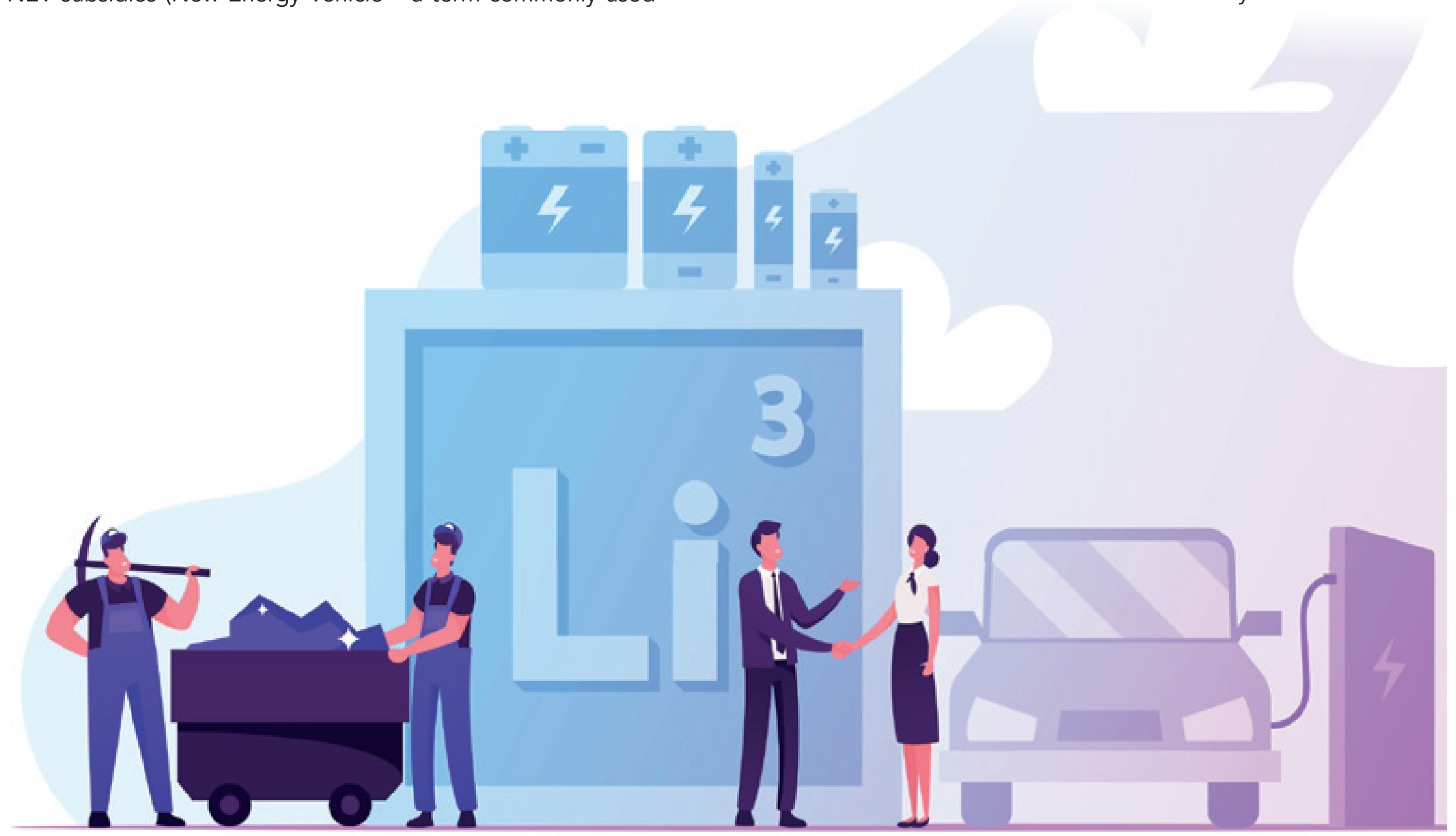
The scheme introduced in 2015 offered subsidies for Chinese EVs produced using government recommended lithium-ion suppliers.

This list excluded foreign firms and contributed to the growth of China's battery sector[11].

Nonetheless, in 2019 with the industry maturing, China scrapped the recommend list of suppliers, allowing foreign lithium-ion manufacturers to enter the Chinese market[12].

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.



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[10] Shell Foundation, 'Energy storage trends for off-grid services in emerging markets, September 2018

[11] https://www.ft.com/content/8c94a2f6-fdcd-11e6-8d8e-a5e3738f9ae4

[12] http://www.chinadaily.com.cn/cndy/2019-07/01/content_37486372.htm

The energy access crisis in Sub-Saharan Africa has been greatly improved by OGS but the sector is at risk of undermining it's environmental credentials by creating a new environmental challenge in the region. Recent news has highlighted the e-waste blight that is damaging the environment and public health in developing countries[13].

Electric and electronic products (including off-grid solar products) are being disposed of inappropriately, with lead-acid and lithium-ion's being the main culprits.

Despite the absence of legal obligations, many companies in the sector have been proactive through collaboration with local partners and trials of the collection and take back of products. Much work is still needed for active retrieval 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 are the implementation of e-waste regulations.

4.1 Regulations Addressing the End-of-life of Lithium Batteries in Europe

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) came into force in 2006 and is transposed in national law by each Member State. In terms of lithium-ion recycling, the producer carries an extended responsibility and must bear the cost of collecting, treating, and recycling, irrespective the economic viability of the process itself. In addition, the Directive requires a minimum recycling efficiency. All collected and identifiable spent batteries must be treated and recycled with the state-of-the-art technologies.

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 regulations for traction batteries,
- Uniform regulations for the calculation of recycling quotas[14].

In all European Economic Area countries, producers are currently held financially responsible for waste battery collection schemes. The organisational responsibility for the schemes and the responsibility for decisions related to which waste battery operations to fund varies between member states[15].

In a growing number of African and Asian countries, dedicated legislation on collection and recycling of waste from electronic products and batteries is being developed[16]. This means that soon producers will be financially responsible to ensure proper collection and recycling.

4.2 Recycling Technologies for Lithium Batteries

4.2.1 Material Supply

The combination of increased lithium-ion demand, geographical concentration of lithium, cobalt and graphite and supply limitations will put pressure on the battery markets in future. Bolstering the recycling of spent lithium-ion is therefore an essential option to improve the circular economy, which in turn will ensure supply and mitigate price fluctuations in materials critical for lithium-ion technologies.

Although, even if all types of lithium-ion become equally recyclable, recycling is unlikely to be pursued on a mass scale unless the prices of raw materials (cobalt and nickel in particular) are equal to or greater than the recyclates[17]. Alternative materials for cathode chemistries, such as lithium-sulphur are being explored – these new cathode chemistries could eventually result in a higher degree of material complexity, which could replace cobalt with manganese, either partially or completely[18].

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[13] https://www.nytimes.com/2019/05/12/climate/electronic-marvels-turn-into-dangerous-trash-in-east-africa.html

[14] Industrial Recycling of Lithium-Ion Batteries—A Critical Review of Metallurgical Process Routes (2020), https://www.mdpi.com/2075-4701/10/8/1107

[15] https://www.epbaeurope.net/wp-content/uploads/2016/12/Perchards_Sagis-EPBA_collection_target_report_-_Final.pdf

[16] https://www.gsma.com/mobilefordevelopment/cleantech/e-waste/

[17] Ahmad Mayyas, Darlene Steward, Margaret Mann, The case for recycling: Overview and challenges in the material supply chain for automotive li-ion batteries, Sustainable Materials and Technologies, Volume 19, 2019, e00087, ISSN 2214-9937, https://doi.org/10.1016/j.susmat.2018.e00087.

[18] Velázquez-Martínez; Valio; Santasalo-Aarnio; Reuter; Serna-Guerrero (2019): A Critical Review of Lithium-Ion Battery Recycling Processes from a Circular Economy Perspective. In: Batteries 5 (4), S. 68. DOI: 10.3390/batteries5040068

Another concern is the environmental impact of lithium-ion production itself. In 2019, an estimate of 61-106kg CO_2-eq/kWh was calculated for NMC chemistry lithium-ion produced using an electricity mix from renewables and fossil fuels[19]. These life cycle assessments tend to be 20% lower in Europe and the US compared to Asia where coal remains the predominant electricity supplier in the region[20]. There is progress elsewhere though: Swedish battery manufacturer Northvolt, is building a Gigafactory that will be powered by 100% clean energy.

It has also pledged to produce batteries up to 90% recyclable where up to 95% of precious metals recovered will be re-used in their battery production, thus delivering an exemplar blueprint for the whole industry[21].

The challenge here is getting the OGS sector access to this type of battery manufacturer.

As mentioned in Chapter 3, OGS companies struggle to compete with larger industries in battery procurement. This means that the off-grid sector will continue to use low-quality LFP that has uneconomical material recovery (meaning it is difficult to recycle).

4.2.2 Cost of Recycling

The focus of the lithium-ion recycling processes is driven by market value of recoverable materials, with cobalt and metallic fractions as the current economic drivers.

At industrial level, recycling processes target LCO and NMC chemistries, both of which are highly profitable due to their high cobalt and nickel content. Not all lithium-ion chemistries pose the same interest for recycling.

The low value of the elements comprising the active material of LMO and LFP electrodes make their recycling uneconomical[22,23]. Materials such as lithium compounds, electrolyte, plastics, and organic materials, are largely lost in most battery recycling facilities, except in China and South Korea, where lithium is recovered as $LiCO_3$.

The toxicity, environmental risk, and sustainability considerations also require the development of suitable treatments for these batteries, especially in developing nations.

4.2.3 Recycling Processes

Lithium-ion end-of-life management after collection of spent batteries typically comprises pre-processing and mechanical, hydrometallurgical, and pyro-metallurgical recycling steps. In the pre-processing step, spent batteries are sorted from mixed waste streams according to their type (typically Li-ion, NiMH, NiCd, alkaline).

The mechanical step involves different processes applied to liberate, classify, and concentrate materials without changing their chemistry. After mechanical processing, the material obtained is refined through pyrometallurgy, hydrometallurgy or a combination of both.

Pyrometallurgy (smelting) is the most common recycling method for end-of-life batteries and refers to operations at elevated temperatures where redox reactions are activated to smelt and purify valuable metals, such as nickel, cobalt and copper, while metals with high oxygen affinity (such as lithium, manganese, aluminum) are lost in the slag.

Hydrometallurgical recycling uses aqueous solutions to recover and extract valuable metals from minerals or inorganic compounds and to break down components into molecular compounds.

The process is generally divided into the three general processes leaching, solution concentration and purification, and metal recovery.

Hydrometallurgy has better quality products and better control over process-related environmental impacts, compared to pyrometallurgy. Besides nickel, cobalt and copper, this process is also used to recover manganese, lithium, phosphorous, and aluminium.

Some facilities apply integrated pyro- and hydrometallurgical process steps in sequence to utilize the benefits of both and thus increasing the number of metals recovered.

Table 1 provides a comparative breakdown of hydrometallurgical and pyrometallurgical recycling processes.

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[19] Swedish Energy Agency, 'Lithium-Ion Vehicle Battery Production', 2019

[20] Carbon Brief, 'Factcheck: How electric vehicles help to tackle climate change' by Zeke Hausfather, Updated 7/2/2020

[21] https://northvolt.com/stories/industrializing-battery-recycling

[22] Progress and Status of Hydrometallurgical and Direct Recycling of Li-Ion Batteries and Beyond (2019), https://www.mdpi.com/1996-1944/13/3/801

[23] Kevin M. Winslow, Steven J. Laux, Timothy G. Townsend, A review on the growing concern and potential management strategies of waste lithium-ion batteries, Resources, Conservation and Recycling, Volume 129, 2018, Pages 263-277, ISSN 0921-3449, https://doi.org/10.1016/j.resconrec.2017.11.001.

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

	Technology	
	Pyrometallurgy	**Hydrometallurgy**
Recovered materials	Ni, Co, Cu	Ni, Co, Cu, Mn, Li, P, Al
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	- Recyclers charge to accept material with reduced cobalt content - Metals with high oxygen affinity (such as Li, Mn, Al) are irrecoverably lost in the slag - Indispensable off-gas cleaning and off-gas monitoring of remaining organics, fluorine and heavy metal nano-powders - Large capital expenditure is necessary for an economical industrial-scale smelting plant (much of cost due to gas treatment) - Additional processing needed to separate metals - Not useful for LFP	- Low variety on input composition required - Minor changes of input materials and impurities (such as specifically halogenates, carbon, hydrocarbon) result in undesirable reactions and significant decline of metal recovery efficiency - Wastewater treatment needed - Expected high cost due to large consumption of chemicals - Requires size reduction - Acid breaks down cathode structure - Solvent extraction needed to separate Co and Ni (or use mixture)

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[24] Accurec 2015: Comparative Study on Li-ion Battery Recycling Technologies, CloseWEEE unpublished report

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)

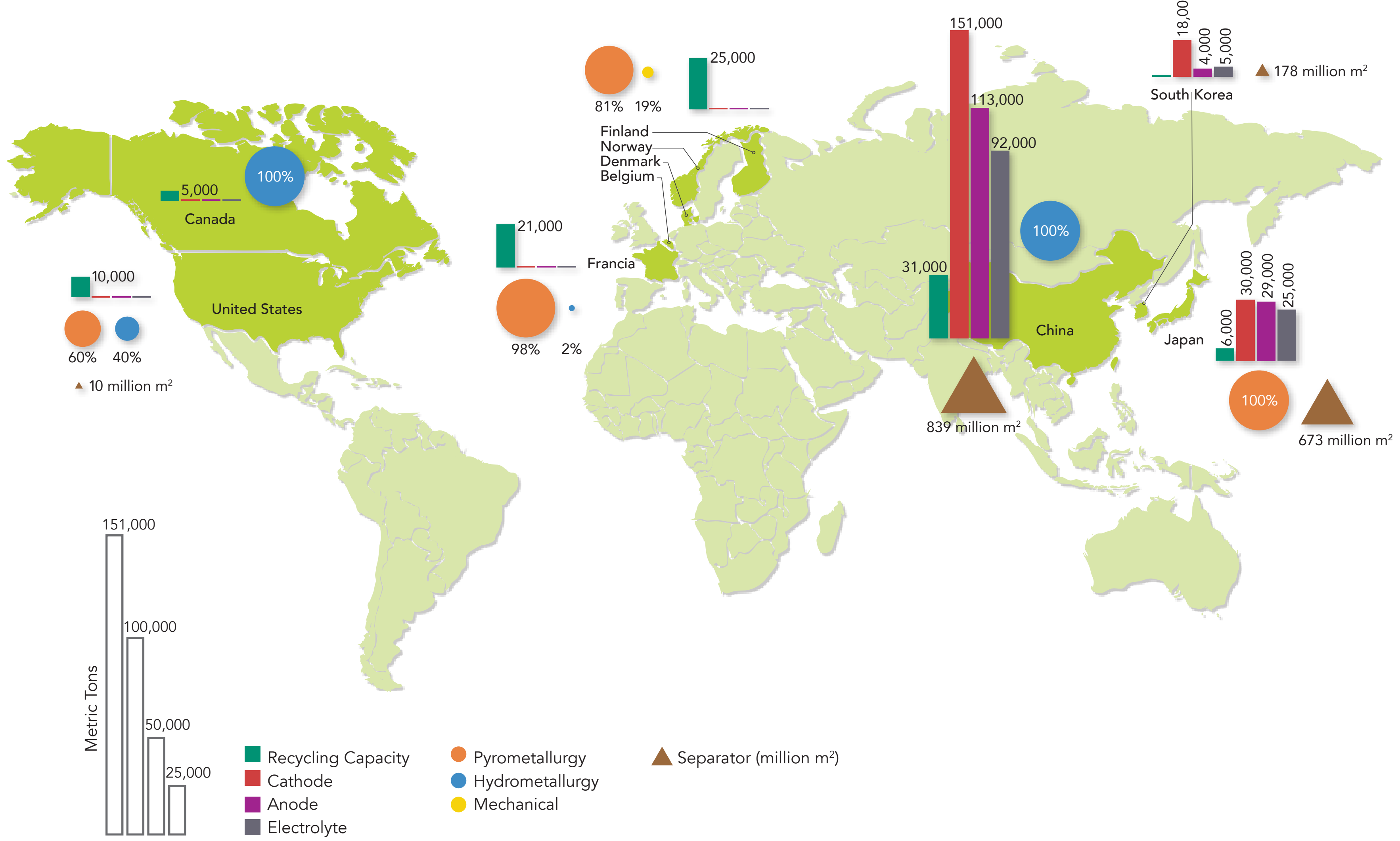

Table 2: Summary of lithium-ion recycling processes and capacities (based on Velázquez-Martínez et al. 2019, Lebedeva et al. 2016, Accurec, 2015)

Company (HQ location)	Recycling facility location	Battery types	Process	Recycling volume, tons of batteries per year/estimated capacity of the facility
Europe				
Valdi (ERAMET) (FR)	Commentry (FR)	Various including Li-ion	Pyrometallurgical	20.000
Umicore Battery Recycling (BE)	Hoboken (BE)	Li-ion, NiMH	Pyrometallurgical	7.000
Glencore	Sudbury (CA) Rouyn-Noranda (CA) Kristiansand (NO)	Li-ion	Pyrometallurgical with H treatment of the slag and electrowinning	7.000
Akkuser Oy (FI)	Nivala (FI)	NiCd, NiMH, Li-ion, Zn alkaline	mechanical	1.000 (Li-ion) 4.000
Accurec Recycling GmbH (DE)	Mülheim (DE), Krefeld (DE)	NiCd, NiMH, Li-ion	Pyrometallurgical with Hydrometallurgical	1.500-2.000
SNAM (FR)	Saint Quentin Fallavier (FR)	NiCd, NiMH, Li-ion	Pyrometallurgical + mechanical separation + Hydrometallurgical to extract Co and Ni	300
Batrec Industrie AG (CH)	Wimmis (CH)	Li	Pyrometallurgical + mechanical treatment	200
Euro Dieuze / SARP (FR)	Dieuze	Li-ion	Hydrometallurgical	200
Recupyl S.A. (FR)	Grenoble (Fr) Singapore (SG)	Li-ion	Hydrometallurgical	110
AEA Technology (UK)	Sutherland (UK)	Li-ion	Hydrometallurgical	n/a
G&P Batteries (UK)	Darlaston (UK)	Various including Li-ion		n/a
North America				
Retriev	Trail, BC (CA)	Li metal, Li-ion	Hydrometallurgical	4.500
AERC Recycling Solutions (US)	Allentown, PA (US) West Melbourne, FL (US) Richmond, VA (US)	All types, including Li-ion and Li metal	Pyrometallurgical	n/a
Japan				
JX Nippon Mining and Metals Co.		Various, including Li-ion	Pyrometallurgical	5.000
Dowa Eco-System Co. Ltd. (JP)		Various, including Li-ion	Pyrometallurgical	1.000
Sony Electronics Inc. – Sumitoma Metals and Mining Co. (JP)		Li-ion	Pyrometallurgical	120-150
Nippon Recycle Center Corp. (JP)	Osaka (JP) Aichi (JP) Miyagi (JP)	NiCd, NiMH, Li-ion, alkaline	Pyrometallurgical	n/a
China				
Shenzhen Green Eco-manufacturer Hi-Tech Co. (GEM) (CN)	Jingmen, Hubei (CN)	NiMH, Li-ion	Hydrometallurgical	20.000-30.000
Hunan BRUNP (CN)	Ningxiang, Changsha, Hunan (CN)	Various including NiMH and Li-ion	Hydrometallurgical	3.600-10.000 >6.000

In the current context donors consider some of the key elements involved in the battery market and the off-grid solar sector: when considering the trajectory of the sector, the supply chain and the types of batteries involved, it is clear that in developing countries, change is needed to increase the sustainability of supply and handle the growing volume of waste batteries impacting the environment and public health.

1. **Sustainability of supply** from an operational perspective would mean companies having access to production facilities that ensure a lower environmental impact, potentially integrating recycled material. From a financial perspective, ensuring a low cost per Wh and access to stable battery producers will ensure business continuity.

2. **End-of-life management** needs to be integrated into all energy access programmes, particularly when it comes to batteries introduced in countries where there is 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 go further than simply asking partners to state whether they have an end-of-life policy but should ensure the end-of-life financing is planned since the early stages.

3. **Proper financing mechanisms** are required to cover the costs of lithium-ion recycling (particularly for chemistries other than NMC and LCO). Safe handling and transportation training to reduce fire-hazard risk is also essential for the health and safety of those on the frontline of the e-waste challenge.

4. **Local Infrastructure needs to be established** to ensure proper collection and handling of batteries.
   As far as treatment is concerned there are a few options that might be considered:

   a. **Ensure proper channelling of lithium-ion** to current recycling infrastructure is available, 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 pyromettallurgical processes, as hydrometallurgical processes have limits to volumes and economies 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 the development of new processes or changes in the offer.

   d. **Dispose of the batteries, if environmentally sound landfills are available locally.** From a resource management perspective, this should only be considered as a last resort, despite being, from a purely economic perspective, the least expensive option in the current context.

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