CLEVE HILL SOLAR PARK

OTHER DEADLINE 4 SUBMISSIONS
WRITTEN REPRESENTATION BY THE APPLICANT - AIR QUALITY IMPACT ASSESSMENT - BATTERY FIRE

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Revision A

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CLEVE HILL
SOLAR PARK

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1 INTRODUCTION

1. This Air Quality Impact Assessment ('AQIA') has been prepared by Arcus Consultancy Services Ltd for Cleve Hill Solar Park Ltd ('CHSPL') to support the Development Consent Order ('DCO') application for Cleve Hill Solar Park ('the Development').

1.1 Structure of the AQIA

2. This AQIA report utilises the following structure:

- Section 1 provides an introduction, including the background to the report and details of contributors;
- Section 2 provides a review of the assessment undertaken by Dr Erasin;
- Section 3 provides the results of the AQIA undertaken by Arcus; and
- Section 4 provides a comparison and conclusion.

3. Three appendices are provided:

- Appendix A - Dr Erasin's detailed modelling report
- Appendix B - Faversham News article dated 15 August 2019
- Appendix C - Emissions Parameters supplied by Leclanché SA

1.2 Background

4. As part of the examination of the application for the Development, a member of the public, Dr Bruno Erasin, has submitted a written summary of an oral submission presented at Open Floor Hearing 2 [REP3-059] which relates to the potential air quality impacts of a battery fire at the energy storage facility which forms part of the Development.

5. In addition to that representation, a more detailed assessment report was issued to Kent Online and forwarded to CHSPL for comment (Appendix A). This document formed the basis of press reports published in the Faversham News on 15 August 2019 (Appendix B). The more detailed assessment report provides further detail relating to the same findings that were presented orally and in written summary to the examination.

6. The Applicant has submitted an Outline Battery Fire Safety Management Plan (OBFSMP) at Deadline 4 (document reference 12.5.1) which sets out design and mitigation measures to prevent, detect, suppress and mitigate potential fire risk at the energy storage facility. In summary, a battery fire is unlikely to occur at the Development and if it were to occur, detection and suppression measures would minimise the effect and any emissions to the environment.

7. Notwithstanding this, the Applicant has prepared this AQIA report as an appraisal of air quality emissions associated with a potential lithium ion battery fire, based on parameters supplied by a technology provider for battery storage, Leclanché SA (see section 1.4) to address Dr Erasin's submission. The parameters supplied to the Applicant are provided in Appendix C. Of the substances emitted, Hydrogen Fluoride (HF) and Carbon Monoxide (CO) are the only two subject to environmental limit values with respect to human health, and are therefore the focus of the AQIA.

1.3 AQIA Author

8. Arcus, the author of this AQIA report, has completed over 50 air quality impact assessments for planning applications for a range of development types, including roads, gas peaking plants, distilleries, CHP boilers and other combustion processes, assessing effects on residential and ecological receptors. Arcus has confirmed with Cambridge Environmental Research Consultants (CERC), manufacturers of industry standard Atmospheric Dispersion Modelling System (ADMS) software, that the version of ADMS

possessed by Arcus is appropriate for modelling short-term releases of less than 24 hours as would be the case here[1]. Further detail on the use of the software is provided in section 3.

9. Dr Paul Phillips leads Arcus' air dispersion modelling team. Dr Phillips has led air quality modelling of emissions from cement and lime kilns, combustion and waste plants, odour from oil pipeline pumping stations and catastrophic failure of liquid oxygen storage, as well as the air quality impact of more conventional developments.

1.4 Technology Provider

10. Leclanché SA is a world leading provider and manufacturer with over a hundred years experience of high-quality energy storage solutions. It's principal focus and expertise relates to lithium-ion cell technologies.

11. Data provided by Leclanché SA details the substances released during a Lithium-Ion battery fire and quantifies the mass of each released assuming the fire suppression system fails and a fire is allowed to propagate. Data is provided for the burning of 5 racks simultaneously and the total release if all 32 racks within a container were to burn down. A rack consists of a metallic cabinet containing 12 modules connected with power and communication wiring. A diagram showing the arrangement of the 32 racks, divided into 4 banks, within a container is shown in Appendix E.

12. Analysis conducted by Leclanché on a Lithium Nickel Manganese Cobalt Oxide (G/NMC) battery at the Institut National de l'Environment Industriel et des Risques has been used to inform the proposed emissions data[2]. The data provided has been verified by comparison to a similar study undertaken by RECHARGE, the European Association for Advanced Rechargeable Batteries which is included in Appendix F.

2 REVIEW OF DR ERASIN'S ASSESSMENT

13. In his submissions, Dr Erasin estimates and models the potential emission and dispersion of hydrogen fluoride (HF) from a hypothetical fire at a large-scale (10 MegaWatt-hour, MWh) lithium-ion (Li-Ion) battery, and compares this with derived exposure levels.

14. Dr Erasin has made estimates of emissions of HF from a grid-scale battery storage facility by scaling up from laboratory-controlled fires in smaller Li-Ion batteries, which do not have fire control measures in place. The hypothetical scenario being considered is therefore unrealistic and would not occur in practice.

15. The modelling undertaken by Dr Erasin used the National Oceanic and Atmospheric Administration (NOAA) Areal Locations of Hazardous Atmospheres (ALOHA) computer programme[3].

16. The ALOHA model is designed to be a quick and easy to use model for the determination of threat zones in real time emergency situations, as such:

"ALOHA's calculations represent a compromise between accuracy and speed."[4]

17. The ALOHA model is designed to give quick, initial results. Such screening tools generally take a precautionary approach when using approximations in modelling, to avoid the risk of missing potentially important effects. The next step, when such a screening tool identifies potentially important effects, is to model them in more detail using a more advanced modelling software, such as the software provided by CERC, as set out in this AQIA report.

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[1] Pers. Comm. telephone call Adam Price, Arcus to CERC, 12 August 2019
[2] This analysis was undertaken for a commercial client and is therefore not publicly available.
[3] Downloaded for free from https://www.epa.gov/cameo/aloha-software on 12/08/2019
[4] ALOHA Data sheet https://response.restoration.noaa.gov/sites/default/files/aloha.pdf accessed on 13/08/2019

18. The model settings reported by Dr Erasin have been used in the ALOHA software and re-run by Arcus, and the results reported by Dr Erasin have been duplicated in order to ensure their validity.

2.1 Data Sources and Assumptions

19. Dr Erasin's data on emissions of HF draws specifically from the study by Larsson et al (the "Larsson study").[5] into emissions of toxic gases from Li-Ion batteries, noting that they:

> *"published data detailing that during battery fires intense heat and considerable amounts of gas and smoke are generated. The results of this investigation have shown (using two independent measurement techniques) that large amounts of hydrogen fluoride (HF) may be generated, ranging between 20mg to 200mg per Wh of normal battery capacity. Additionally, another potential toxic gas, phosphoryl fluoride (POF3) was measured on some fire test runs measuring 15-22mg/Wh".*

20. The Larsson study is based on Li-Ion batteries that contain lithium hexafluorophosphate ($LiPF_6$) and reports tests on batteries of between c. 90 and 140 Watt-hours (h). The authors of the study note a poor correlation between capacity of the battery in Wh and the amount of HF released, with a factor of 10 in the difference between the highest and lowest releases (paragraph 3, Lithium-ion battery fire tests section). The authors hypothesise potential reasons for this, but without testing or conclusion. A containerised, grid-scale, Li-Ion battery such as those proposed to be utilised at the Development can have a capacity in excess of c. 1,000,000 Wh, and therefore the use of the Larsson study for extrapolation purposes, as carried out by Dr Erasin, involves the same uncertainty for much larger potential values, leading to a greatly increased range of potential emissions. The Larsson study authors note that:

> *"energy release from a internal cell event in a confined environment can, for example, be lower than the energy release from the same cell in case of external fire";*

21. As the only type of fire considered plausible for the Development would be internally generated (i.e., by the battery itself), this suggests that the results on the lower end of the range found by Larsson et al. are more likely to be appropriate.

22. Finally, the batteries experimented with by Larsson et al were small (up to a nominal 140 Wh), with no fire suppression or heat management in place; the authors conducted a "limited" study of applying water mist, but were attempting to do this without suppressing the fire, and could not draw any conclusions on whether this affected the overall production of HF.

23. Therefore, the Larsson study is of very limited application for a grid-scale energy storage development and cannot be taken as a true indication of potential toxic gas release from a fire at the Development.

2.2 Hydrogen Fluoride Exposure Limit

24. Comparison has been made by Dr Erasin (paragraph 1, Exposure Limits section, Appendix A) to the workplace exposure limit as set out in EH40/2015[6]. For HF this is 1.8 parts per million (ppm), to which a safety factor of 1/100 has been applied, to arrive at a public exposure limit of 0.018 ppm.

[5] Larsson et al. (2017). Toxic fluoride gas emissions from lithium-ion battery fires. Scientific Reports 7, Article number: 10018 (2017). Available at: https://www.nature.com/articles/s41598-017-09784-z [accessed on 15/08/2019].
[6]Available online through HSE http://www.hse.gov.uk/pubns/priced/eh40.pdf accessed on 12/08/2019

25. The workplace exposure limit represents the long-term exposure limit (LTEL), which is taken across an 8-hour reference period, and applies to individuals working in close proximity to HF on a daily basis. This level is the maximum that workers should be exposed to on a long-term basis. The scaling to convert this to a public exposure limit is appropriate for long-term exposure levels.

26. As noted in section 1.2, paragraph 6, the OBFSMP will ensure that the design of the energy storage facility, as well as the fire detection and suppression controls, will prevent a fire, and prevent fire propagation therefore ensuring that the long-term release of significant quantities of HF from the Development would not occur. As such, the use of a long-term exposure limit for examining potential effects is not appropriate in this case.

27. Short term general population exposure limits are provided in the form of Acute Exposure Guideline Levels (AEGLs). These are limits used by emergency planners and responders as guidance in dealing with accidental release of chemicals into the air[7], and are put forward in Public Health England's guidance on the incident management of accidents involving HF and Hydrofluoric Acid[8] and Carbon Monoxide[9]

28. AEGLs are provided for a range of short-term time-scales, and using the 1 hour burn duration described by Dr Erasin (paragraph 2, Dispersion Modelling of HF Release section in Appendix A) provides the limit values presented in Table 1. Limit values are also included for Carbon Monoxide as this is included in the dispersion modelling carried out by the Applicant:

Table 1: AEGL Limit values for Hydrogen Fluoride and Carbon Monoxide

AEGL Limit	HF	CO
AEGL-1	1	NR
AEGL-2	24	83
AEGL-3	44	330

29. AEGL-1 is described as *"the level of chemical in the air at or above which there may be notable discomfort, irritation, or certain asymptomatic non-sensory effects. However the effects are not disabling and are transient and reversible upon cessation of exposure".* An AEGL-1 limit for CO is not recommended (NR) due to a lack of data[10].

30. AEGL-2 is described as "*the level of chemical in the air at or above which there may be serious long-lasting effects or impaired ability to escape*".

31. AEGL-3 is described as *"the level of chemical in the air at or above which there may be life-threatening health effects or death".*

32. AEGL-2 is the relevant exposure level to consider in relation to a short-term emergency release of HF or CO on the general public, as this is the level at which exposure becomes unacceptable, even for a short-duration, highly improbable or infrequent event.

33. Therefore, the appropriate limit concentration for HF is considered to be 24 ppm, which is 1,333 times higher than that used by Dr Erasin in his assessment. The appropriate limit concentration for CO is considered to be 83 ppm.

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[7] https://www.epa.gov/aegl/about-acute-exposure-guideline-levels-aegls accessed on 13/08/2019
[8] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/659083/Hydrogen_fluoride_incident_management.pdf accessed on 12/08/2019
[9] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/825202/Carbon_monoxide_incident_management_PHE.pdf accessed on 29/08/2019
[10] https://www.epa.gov/aegl/carbon-monoxide-results-aegl-program accessed on 28/08/19

2.3 Modelled Emissions

34. Emissions of HF from a fire in a Li-Ion battery have been estimated by Dr Erasin as being 200 kg to 2,000 kg (paragraph 1, Extrapolation of Hydrogen Fluoride Dispersion section, Appendix A).

35. Data provided by battery supplier Leclanché SA gives the realistic worst-case scenario of HF emissions from a battery fire as 2.07 kg. This assumes that the fire suppression system does not work and the fire propagates from rack to rack (with 5 racks burning simultaneously) inside the container.

36. This value is 1.04% of the lower band of Dr Erasin's estimate of emissions (200 kg), and 0.08% of the greatest emission value (2,520 kg) used in the ALOHA modelling scenarios.

37. Arcus' modelling has assumed a fire, and therefore release, duration of 1 hour, however the installed fire suppression system would suppress a fire in less time and the emergency services would also be anticipated to respond to such an incident in less than 1 hour.

2.4 Dr Erasin's Modelling Results

38. Appendix I of Dr Erasin's report provides details of the models run and the corresponding results. There are 4 parameter sets for runs of the ALOHA model provided, but only 3 charts of results presented. In this analysis it has been assumed, based on replication of the results by Arcus, that the charts correspond to the modelling parameters below them.

39. Dr Erasin's four model scenarios are, in summary:

    1. 252 kg/hr for 60 minutes (results not reported);
    2. 2,520 kg/min for 60 minutes;
    3. 2,520 kg/hr for 60 minutes; and
    4. 2,520 kg in 1 minute.

40. As noted above, Dr Erasin's report shows resulting charts for only scenarios 2, 3 and 4.

41. Scenario 2, which represents the worse-case scenario and is that from which Dr Erasin has drawn headline conclusions, includes an emission rate of HF of 2,520 kg/minute for a period of 60 minutes leading to a total emission of 151,200 kg. This contrasts with the total emissions estimated by Dr Erasin as being a maximum of 2,000 kg (paragraph 1, Extrapolation of Hydrogen Fluoride Dispersion section, Appendix A), i.e. the modelled release is approximately 75 times the estimated maximum. This inconsistency is not explained.

42. Scenarios 3 and 4 use a modelled total HF emission of 2,520 kg, which is approximately 1.25 times the estimated maximum, also without explanation.

3 THE APPLICANT'S DISPERSION MODELLING OF HF EMISSIONS

43. The ADMS Roads Extra 4, version 4.1.1 software has been used to assess the impact of potential HF emissions from a Li-Ion battery fire on the environment by calculating the predicted ground level concentrations arising from emissions to atmosphere, based on Gaussian approximation techniques. The worst-case concentrations have been compared with appropriate air quality standards to determine whether the specified limits have been exceeded.

44. ADMS-Roads utilises site-specific hourly sequential meteorological data to enable a realistic assessment of dispersion from point sources to be conducted for weather conditions that occur at the site.

45. CERC, manufacturers of ADMS software, has confirmed that the version of ADMS software being used is appropriate for the assessment of short term accidental release undertaken (see section 1.3).

3.1 Model Parameters

3.1.1 Input Parameters

46. HF and CO emissions estimates and release duration are taken from data supplied by Leclanché SA. Four possible scenarios have been modelled based on the data supplied by Leclanché SA based on the potential scale and duration of any fire. The scenarios are a combination of the results of 5 racks burning simultaneously and of an entire container burning, over a duration of 3 and 5 hours. The worst-case scenario from the four was then taken and assessed against the exposure limits. The four proposed scenarios are detailed in Table 2:

Table 2: Matrix of Scenarios Showing Emission Rates of HF and CO

	3 Hours	**5 Hours**
5 Racks Simultaneously	Scenario 1: 1.189 g/s HF 222 g/s of CO	Scenario 2: 0.714 g/s of HF 172 g/s of CO
32 Racks Total	Scenario 3: 1.207 g/s of HF 222 g/s of HF	Scenario 4: 0.722 g/s of HF 133 g/s of CO

47. Emissions quantities have been supplied by Leclanché SA and are detailed in Appendix C. As a fire is inherently uncontrolled, the exact duration of the emission is unknown, however Leclanché SA propose a burn time for an entire 32 rack container (unabated) to be 3-5 hours. For the scenarios that propose the burn of 5 racks simultaneously, the release duration has been scaled to represent the duration of only 5 of the 32 racks combusting.

48. 5 racks burning simultaneously has been chosen as a scenario as in the event of thermal runaway within the unit, this is the maximum number of racks that would be burning at any one time. While all 32 racks would burn in total (in the absence of any fire suppression) the dynamics of the thermal propagation would mean that only 5 would ever burn simultaneously as when the 6^{th} rack would be beginning to ignite, the first would be burning out.

49. These scenarios represent an unlikely situation, in which a fire starts, is not detected due to a failure of the fire detection system, is not extinguished due to a failure of the fire suppression system, is allowed to propagate within the container and is allowed to burn unabated for an extended duration due to a lack of emergency response.

50. The surface roughness representing the area surrounding the emission should typically be approximately 10 times less than the average obstacle height in metres based on research undertaken by the World Meteorological Organization. Given the height of the surrounding terrain and buildings, and the proposed levels of open space, a surface roughness of 0.5 deemed to be appropriate.

51. As this would not be a controlled emission the exact temperature of gasses being emitted to the atmosphere could be variable. In order to represent the worst-case scenario a range of emissions temperatures have been modelled based on the data provided by Leclanché SA, with the temperature giving rise to the highest HF and CO concentrations used. This was found to be 300^{o}C.

52. The model was run for an entire year of hourly sequential meteorological data taken from London City Airport in 2018, this being the closest available meteorological data. The maximum hourly value at the nearest human receptor (residential dwelling where an extended human presence is expected), determined to be Crown Cottages, was calculated.

3.1.2 Limitations

53. The emissions of HF and CO in the event of all 32 racks burning has been presented assuming that all 32 racks would burn simultaneously for the duration of the fire. As detailed in paragraph 48 this would not occur in reality as the nature of the propagation within the unit means that only 5 racks will ever be on fire at any one time. This would mean that, as the fire progressed through the container, emissions from the fire in the first racks would already be beginning to disperse into the atmosphere by the time the fire reached later racks, reducing the atmospheric concentration of HF and CO. As such, representing the emissions as a result of all 32 racks burning simultaneously presents a substantial overestimate of any atmospheric concentrations as emissions from the burning of every rack are represented in the atmosphere simultaneously, which would not realistically be the case.

54. If the duration of emission is very short then then any emissions would be expected to disperse in 3 dimensions. The model only accounts for two dimensions of dispersion and hence in the event of a very short duration emission, would present an overestimate of concentrations.

55. HF is highly soluble in water, and any periods of high humidity, rain or mist will reduce the airborne concentration as the HF would move readily from the air into the suspended water. This effect would also take place in any water used in fire suppression. As chemical reactions such as the mix of HF with water are not modelled in ADMS, any predicted concentrations would be overestimates.

56. The nearest residential properties are due south of the energy storage compound, at a distance of approximately 200 m. The wind blows in this direction approximately 17% of the time according to the baseline meteorological data from London City Airport. In the unlikely event of any release, therefore, the probability of this coinciding with winds that would blow the emissions towards the nearest properties is approximately 17%.

3.2 Results

57. Predicted concentrations of HF were calculated around the energy storage facility using the worst-case emissions scenario identified to be Scenario 3, detailed in Table 2. The maximum concentration recorded at the nearest residential receptor, Crown Cottages, is 80.0 $\mu g/m^3$ which equates to 0.09 ppm. This is 9% of the AEGL-1 limit, and 0.38% of the AEGL-2 limit. These concentrations represent outdoor concentrations of HF and any indoor concentrations would be substantially lower.

58. Predicted concentrations of CO were calculated around the energy storage facility using Scenario 3. The maximum concentration recorded at the nearest human receptor, Crown Cottages, is 14,718 $\mu g/m^3$ which equates to 17.7 ppm. This is 21.3% of the AEGL-2 limit (there is no AEGL-1 limit - see section 2.2). These concentrations represent outdoor concentrations of CO and any indoor concentrations would be substantially lower.

59. Concentrations of atmospheric HF and CO will decrease with distance from the emission source, therefore the modelled concentrations at Crown Cottages will represent the worst-case concentrations at any human receptors near the Development.

4 CONCLUSIONS

4.1 Limitations of Dr Erasin's Assessment

60. Dr Erasin's report makes clear the assumptions, modelled values and assessment thresholds that have been used. These are all inappropriate or unrealistic, as explained in section 2 and summarised below:

- Control measures to eliminate or restrict a fire and its consequences are not accounted for;
- The exposure limit used is 1,333 times lower than the limit recommended in Public Health England guidance;
- The estimated total emission (2,000 kg) is three orders of magnitude larger than the realistic worst-case scenario provided by Leclanché SA of 2.07 kg; and
- The modelled emission (2,520 kg/min for 60 minutes) is 75 times Dr Erasin's own estimated total emissions (2,000 kg).

61. This has led to a substantial over-estimation of potential impacts, in the event of the unlikely scenario of a failure of the fire detection and suppression system, and a lack of emergency response within 1 hour.

4.2 Findings of the Applicant's AQIA

62. The modelling undertaken by Arcus, using assumptions derived from data provided by Leclanché SA, has shown that in the event of a Li-Ion battery fire which is not controlled by the installed fire suppression system, the worst-case concentrations of HF at the nearest residential properties would be approximately 5% of AEGL-1 (the level above which it is predicted that the general population, including susceptible individuals, could experience notable discomfort, irritation, or certain asymptomatic nonsensory effects. However, the effects are not disabling and are transient and reversible upon cessation of exposure). The worst-case concentrations of CO would be approximately 21% of the AEGL-2 limit. It is worth reiterating that these are overestimates for the reasons given in section 3.1.2.

63. Taking into account the implementation of the fire safety measures set out in the OBFSMP, the Development is unlikely to result in a fire event that would result in the exceedance of Public Health England guidance limits for HF and CO at the closest residential receptors, even in the event of a failure of the fire suppression system and emergency services.

4.3 Comparison of Assessment Methodologies

64. Table 2 provides a comparison of the methodologies employed by Dr Erasin and the Applicant:

Table 2: Comparison of Assessment Methodologies

Comparison	Dr Erasin	The Applicant
Model Used	Areal Locations of Hazardous Atmospheres (ALOHA) Computer model designed to produce reasonable results quickly for use by emergency responders. Provides a compromise between accuracy and speed.	Atmospheric Dispersion Modelling System (ADMS) Roads extra 4, version 4.1.1 Advanced dispersion modelling software used extensively in UK local air quality management and globally for assessment studies of complex situations in urban and large industrial areas.

Comparison	Dr Erasin	The Applicant
Model Input Meteorological Parameters	Estimate of one-time wind speed, direction, relative humidity and cloud cover, relies on user input.	One year of sequential hourly meteorological data supplied by the Met Office.
Emissions Estimate (HF)	Data extrapolated from study of small-scale battery fires. Inherent uncertainty about the relationship between capacity and emission rate included as the results were scaled for a larger battery.	Data supplied based on a realistic worst-case scenario from leading global battery manufacturer based on industrial fire following consecutive safety failures.
Limit Values	Long term workplace exposure limit for those working in close proximity to HF on a daily basis.	Acute emergency exposure limits designed for rare accidental releases of chemicals into the air.

APPENDIX A - DR ERASIN'S DETAILED MODELLING REPORT

Cleve Hill Case Team
1/18 Eagle Wing
The Planning Inspectorate
Temple Quay House
Temple Quay
Bristol
BS1 6PN

20th July 2019

Ref: 20018862

Cleve Hill Solar Park Development – Human Health and Environmental Risks - Objections

Dear Madam or Sir,

I would like to express my objection to the Cleve Hill Solar Park development based on the limited and insufficient Human Health Risk Assessment and Environmental Risk Assessment presented to the Planning Inspectorate during the initial planning application process to date.

Summary

It is my opinion that the following conclusions can be drawn from the preliminary assessments conducted:

- Technical study demonstrated release of toxic and harmful hydrogen fluoride gas from lithium batteries in an event of fire;
- Reports have been published that fires from lithium chloride batteries can be prolonged, explosive and difficult to control;
- Use of dispersion model developed by US Environment Protection Agency indicate that significant concentrations of hydrogen fluoride may spread over a significant distance;
- Expected hydrogen fluoride concentrations may exceed derived domestic exposure limits by a factor of 2,444 at a distance of 4.5km, a factor of 1,333 at a distance of 7.8km and a factor of 55 at a distance of 10km.
- It was concluded that human health risk in a catastrophic fire event of a 10,000kWh battery storage system causes a foreseeable and significant risk to a large number of the population around the Cleve Hill Solar Park Development.
- Significant concentrations of copper and nickel, among other heavy metals, have been determined in the metallic leachates from various types of lithium batteries according to various standard leachate procedures.
- Copper concentrations ranged between 54,100 mg/kg to 278,000mg/kg of battery material.
- Based on a 100,000kg battery storage system there is a potential to release 6,670kg of copper in a catastrophic event.
- The volume of water in a catastrophic flooding event of 0.5m of the entire area is estimated to be approximately 1,750,000m^3.
- The calculated potential concentrations of copper in the water would be approximately 3.81mg/L.

- Based on an Environmental Quality Standard of 0.001 mg/L for copper, the estimated concentration from a pollution event from the battery storage area would exceed by a factor of 3,810.

Based on the foreseeable and significant human health risks and environmental pollution risks from the proposed battery storage systems for the Cleve Hill Solar Park, it is recommended that any such battery storage system should be at least 15km from any population.

Synopsis

The Cleve Hill Solar Park Planning Statement, dated November 2018, states that the proposed development is 491.2 ha comprising an array of solar PV modules, energy storage and associated infrastructure. However, few technical details are provided of the size, dimensions, volume and weight of the actual energy storage units required to capture and store the energy produced.

There are well-documented significant risks associated with large scale energy storage units, including the risk of fire, and leaching of heavy metals into the environment during catastrophic events.

In 2018 AIG Energy Industry Group reviewed lithium-ion battery energy storage systems and commented that 'battery fires are often very intense and difficult to control. They can take days and or even weeks to extinguish properly'; 'internal battery short circuits which lead to internal battery heating, battery explosions and fires'; can cascade to surrounding batteries, resulting in a larger scale fire'; 'however, inert gas and foam suppression systems seem unable to control thermal runaway, so the two main options are likely to be automatic fire sprinklers and water mist'.

In the following report I have provided potential scenarios of catastrophic events, potentially exposing residents in close proximity to the proposed development and the potential pollution impact on the control surface water and consequential adverse impact on vegetation and fauna. Occurrence of such catastrophic events over an anticipated 40-year operational period can not be excluded and should not be ignored during the current phase of the planning application review.

Human Health Risk – inhalation of toxic fumes

Recent studies conducted by Larsson *et al*., 2018 published data detailing that during battery fires intense heat and considerable amounts of gas and smoke are generated. The results of this investigation have shown (using two independent measurement techniques) that large amounts of hydrogen fluoride (HF) may be generated, ranging between 20mg to 200mg per Wh of normal battery capacity. Additionally, another potential toxic gas, phosphoryl fluoride (POF3) was measured on some fire test runs measuring 15-22mg/Wh.

Health Effects of Hydrogen Fluoride

Hydrogen fluoride is very toxic by inhalation at high concentrations and corrosive to the respiratory tract and skin.

Extrapolation of Hydrogen Fluoride Dispersion

Extrapolating these values reported by *Larsson et al.,* 2018, for a large scale energy storage unit which may range from a 1000kWh to a 10,000kWh battery storage system, which may be used for the Cleve Hill Solar Park development, a potential release of 200kg to 2000kg of hydrogen fluoride may be expected in the case of an event of fire/explosion.

Dispersion Modelling of Hydrogen Fluoride Release

Paul *et al.,* 2014, recently published a technical research paper reviewing a dispersion model of accidental release of Chlorine gas using the ALOHA (Areal Locations of Hazardous Atmospheres) modelling tool. The ALOHA software was originally produced by the US Environmental Protection Agency, which is freely available on the internet.

Various scenarios were run using the ALOHA model assuming a 1000kWh and 10,000kWh battery storage system in an event of fire releasing hydrogen fluoride. In the simple dispersion model it was assumed that a moderate breeze was present and hydrogen fluoride gas released over a short period (1 minute release) or over a 60 minute release time.

Diagrammatic Presentation of Hydrogen Fluoride Release

The visual diagrams and input parameter for a limited number of scenarios run are presented in Appendix I and a moderate breeze (5.5-7.9m/s) was used for all scenarios tested.

As shown in the diagrams, based on the various scenarios, the catastrophic release contaminated plume of hydrogen fluoride could reach up to 10 km at concentrations of 1 ppm within 60 minutes. The same scenario may release hydrogen fluoride concentrations of 44ppm at distance of 4.5km within 60 minutes.

Exposure Limits

The workplace exposure limit in the UK is 1.8ppm as detailed in HSE document (EH40/2015). Currently there is no exposure limit for domestic properties in the UK for Hydrogen Fluoride so the Environment Agency procedures recommend using a safety factor of 100, to derive exposure limits for domestic properties. The derived exposure limit for domestic properties is thus 0.018ppm.

Considering the dispersion model using the ALOHA modelling tool, considering the case of a 10,000kWh catching fire and generating hydrogen fluoride for a duration of 60 minutes, the predicted ambient hydrogen fluoride concentrations exceed the derived domestic property exposure limit by a factor of 2,444 at a distance of 4.5km and a factor of 1,333 at distance of 7.8km and a factor of 55 at a distance of 10km.

Preliminary Human Health Risk Assessment

Based on this preliminary assessment using various scenarios and assumptions, it is concluded that the risk to human health in a catastrophic fire event of a 10,000kWh battery storage system is very significant and in my opinion not acceptable to potentially expose a large number of residents in the close vicinity of the proposed development at Cleve Hill Solar Park.

The population both in the easterly direction of the development and westerly/south westerly direction of the development may be exposed to unacceptable risks including residents at Seasalter, Graveney, Faversham and Whitstable.

Heavy Metal Pollution of Controlled Surface Water

The environmental pollution risk in relation to the potential release of heavy metal leaching from the battery storage systems during a catastrophic event has also not been considered in the Cleve Hill Solar Park development planning application.

It is acknowledged that a substantial bund will be constructed around the proposed battery storage systems and transformers, but it is understood that no information of the actual battery storage system has been submitted for the current planning application.

However, over an anticipated operational period of 40 years a catastrophic event case scenario has to be considered, as it is well known that protective measures such as 'bunds' and containments have failed in many other previous cases. In my opinion such a failure of the bund cannot be ignored due to sensitivity of receptors and the potential impact to Controlled Water.

The proposed Cleve Hill Solar Park Development land is surrounded by sensitive controlled water and drainage ditches intercepting the development which are linked to the marsh land habitats and associated fauna and is known to have a high risk of flooding. The flood risk is demonstrated to be taken seriously by Cleve Hill Solar Park as the solar panels are proposed to be installed 1.2m above ground level.

Heavy Metal Leaching Potential from Lithium Chloride Batteries

In a recent technical paper, Kang *et al.*, 2013, assessed the potential environmental and human health impacts of rechargeable lithium batteries. Three standard procedures were used to assess chemical leaching assessment of lithium chloride batteries, which are applicable for testing in the USA and California Department of Toxic Substance Control, including Toxicity Characterisation Leaching Procedure (TCLP), Waste Extraction Test (WET) and the Total Threshold Limit Concentration (TTLC).

Significant concentration of copper and nickel, among other heavy metals, have been determined in the metallic leachates from various types of lithium batteries according to the TTLC procedure.

Copper concentrations ranged between 54,100 mg/kg to 278,000mg/kg of battery material.

Environmental Quality Standard

Environmental Quality Standard for heavy metal pollution for controlled water (Freshwater) ranges from 0.001 to 0.028 mg/L for copper.

Case scenario for potential catastrophic event at Cleve Hill Solar Park Site

Currently, the Cleve Hill Solar Park development have provided no clear information of the size and dimension and weight of the proposed battery storage system. However, for the purpose of undertaking a preliminary assessment of the potential impact of heavy metal pollution on Controlled Water, I assumed a weight of 10,000kg to 100,000kg battery storage system. The assumption is based on reviewing technical information in relation to large scale battery storage systems. There is a considerable possibility that the proposed battery storage systems are in fact substantially larger and heavier.

Calculation of Potential Heavy Metal Pollution Capacity

In a catastrophic, extreme flooding event, the assumption was made that the entire development area and the battery storage area is submerged by 0.5m for a duration of 12 hours to 24 hours. Based on a 100,000kg battery storage system there is a potential to release 6,670kg of copper in a catastrophic event. The volume of water in a catastrophic flooding event of 0.5m of the entire area is estimated to be approximately 1,750,000m^3. The calculated potential concentrations of copper in the water would be approximately 3.81mg/L.

Based on an Environmental Quality Standard of 0.001 mg/L for copper, the estimated concentration from a pollution event from the battery storage area would exceed by a factor of <u>3,810</u>.

Based on this preliminary scenario, which would have to be further developed and verified, a preliminary conclusion can be drawn that the proposed battery storage systems at the Cleve Hill Solar Park could cause a <u>foreseeable</u> and <u>significant</u> environmental risk.

Conclusions

It is my opinion that the following conclusions can be drawn from the preliminary assessments conducted:

- Technical study demonstrated release of toxic and harmful hydrogen fluoride gas from lithium batteries in an event of fire;
- Reports have been published that fires from lithium chloride batteries can be prolonged, explosive and difficult to control;
- Use of dispersion model developed by US Environment Protection Agency indicate that significant concentrations of hydrogen fluoride may spread over a significant distance;
- Expected hydrogen fluoride concentrations may exceed derived domestic exposure limits by a factor of 2,444 at a distance of 4.5km, a factor of 1,333 at a distance of 7.8km and a factor of 55 at a distance of 10km.

- It was concluded that human health risk in a catastrophic fire event of a 10,000kWh battery storage system causes a foreseeable and significant risk to a large number of the population around the Cleve Hill Solar Park Development.
- Significant concentrations of copper and nickel, among other heavy metals, have been determined in the metallic leachates from various types of lithium batteries according to various standard leachate procedures.
- Copper concentrations ranged between 54,100 mg/kg to 278,000mg/kg of battery material.
- Based on a 100,000kg battery storage system there is a potential to release 6,670kg of copper in a catastrophic event.
- The volume of water in a catastrophic flooding event of 0.5m of the entire area is estimated to be approximately 1,750,000m^3.
- The calculated potential concentrations of copper in the water would be approximately 3.81mg/L.
- Based on an Environmental Quality Standard of 0.001 mg/L for copper, the estimated concentration from a pollution event from the battery storage area would exceed by a factor of 3,810.

Recommendations

The following recommendations are made to the Planning Inspectorate:

Based on the foreseeable and significant human health risks and environmental pollution risks from the proposed battery storage systems for the Cleve Hill Solar Park, it is recommended that any such battery storage system should be at least 15km from any population.

It is also recommended that Cleve Hill Solar Park undertake an additional assessment of fire risk and dispersion modelling and verify whether the battery storage system would have to be located in excess of the 15km from any population as detailed above.

This report was prepared by Bruno Erasin, BSc, PhD.

Appendices

Appendix I – Dispersion model scenarios of hydrogen Fluoride

References

Human Health Risks

Fredrik Larsson, Petra Andersson, Per Blomqvist and Bengt-Erik Mellander, Toxic Fluoride Gas Emissions from Lithium-Ion Battery Fires, 2017, Scientific Reports, 7:10018, DOI:10.1038/s41598-017-0984-z

Rajesh Paul, Animesh Mondal, M.A.A. Shoukar Choudhury, Dispersion Modeling of Accidental Release of Chlorine Gas, Proceedings of the International Conference on Chemical Engineering, 2014.

US Environment Protection Agency, Areal Locations of Hazardous Atmospheres (ALOHA) software.

https://www.epa.gov/cameo/aloha-software.

Health and Safety Executive, EH40/2005 Workplace exposure limits. www.hse.gov.uk/pubns/books/eh40.htm.

Lithium-ion Battery Energy Storage Systems, AIG Energy Industry Group, 2018.

Heavy Metal Pollution/Environmental Risks

Daniel Hsing Po Kang, Mengjun Chen and Oladele A. Ogunseitan, Potential Environmental and Human Health Impacts of Rechargeable Lithium Batteries in Electronic Waste. Environmental Science and Technology, 2013, 47, 5495-5503

Environmental Agency, including Environmental Agency R&D Publication 20 (2006) “Remedial Targets Methodology: Hydrogeological Risk Assessment for Land Contamination”.

Environment Agency Groundwater Protection: Policy and Practice, Part 3 – tools (GP3). (August 2013, version 1.1).

The River Basin Districts Typology, Standards and Groundwater threshold values (Water Framework Directive) (England and Wales) Directions 2010.

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SITE DATA:
  Location: AUBURN, WASHINGTON
  Building Air Exchanges Per Hour: 2.23 (unsheltered single storied)
  Time: June 19, 2019  0914 hours PDT (using computer's clock)

CHEMICAL DATA:
  Warning: HYDROGEN FLUORIDE can react with water and/or water vapor.  This
  can affect the evaporation rate and downwind dispersion.  ALOHA cannot
  accurately predict the air hazard if this substance comes in contact with
  water.
  Chemical Name: HYDROGEN FLUORIDE
  CAS Number: 7664-39-3                 Molecular Weight: 20.01 g/mol
  AEGL-1 (60 min): 1 ppm   AEGL-2 (60 min): 24 ppm   AEGL-3 (60 min): 44 ppm
  IDLH: 30 ppm
  Ambient Boiling Point: 18.9° C
  Vapor Pressure at Ambient Temperature: 0.85 atm
  Ambient Saturation Concentration: 867,932 ppm or 86.8%

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
  Wind: 10.7 meters/second from w at 3 meters
  Ground Roughness: open country         Cloud Cover: 5 tenths
  Air Temperature: 15° C                 Stability Class: D
  No Inversion Height                    Relative Humidity: 5%

SOURCE STRENGTH:
  Direct Source: 252 kilograms/hr        Source Height: 0
  Release Duration: 60 minutes
  Release Rate: 4.2 kilograms/min
  Total Amount Released: 252 kilograms

THREAT ZONE:
  Model Run: Gaussian
  Red   : 113 meters --- (44 ppm = AEGL-3 [60 min])
  Orange: 155 meters --- (24 ppm = AEGL-2 [60 min])
  Yellow: 907 meters --- (1 ppm = AEGL-1 [60 min])
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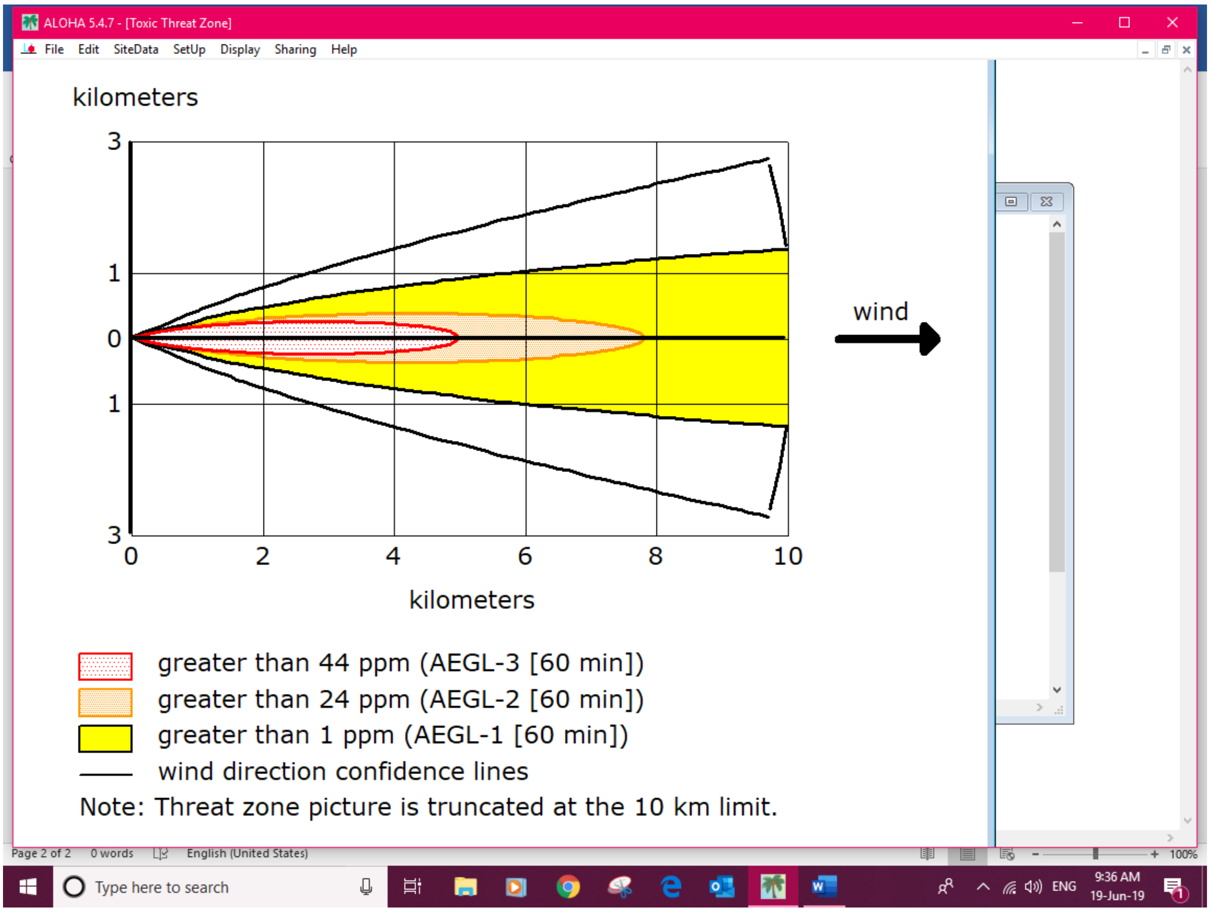
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greater than 1 ppm (AEGL-1 [60 min])
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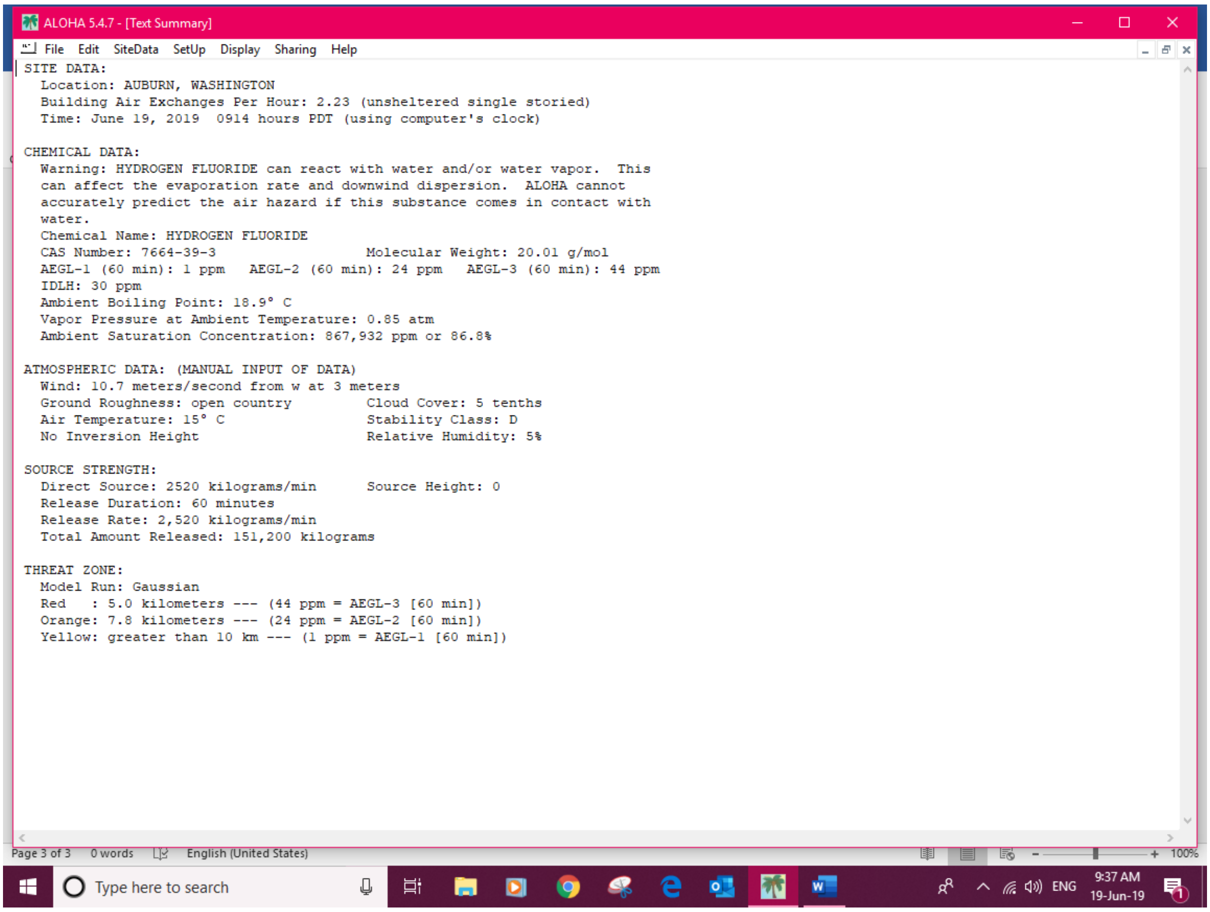

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Building Air Exchanges Per Hour: 2.23 (unsheltered single storied)
Time: June 19, 2019 0914 hours PDT (using computer's clock)

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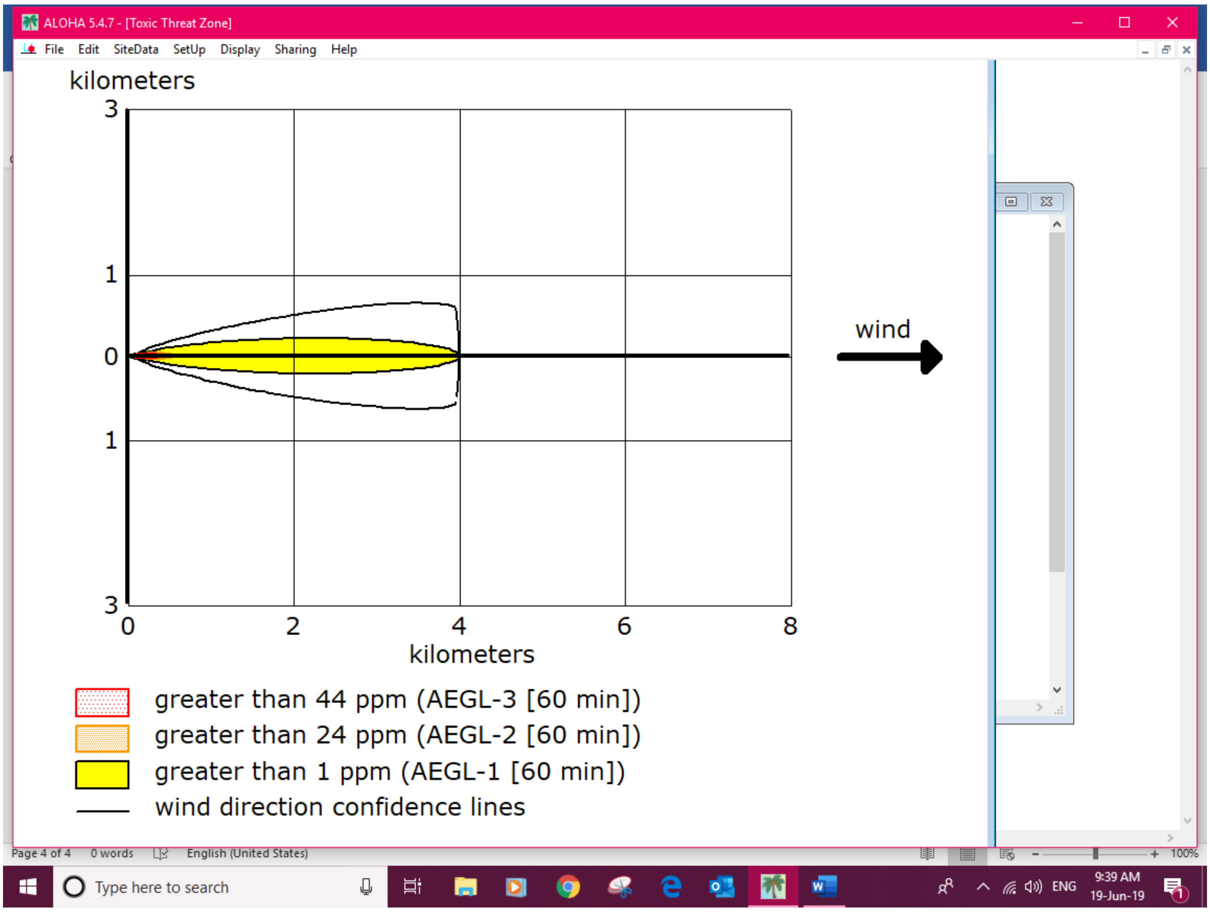
Chemical Name: HYDROGEN FLUORIDE
CAS Number: 7664-39-3 Molecular Weight: 20.01 g/mol
AEGL-1 (60 min): 1 ppm AEGL-2 (60 min): 24 ppm AEGL-3 (60 min): 44 ppm
IDLH: 30 ppm
Ambient Boiling Point: 18.9° C
Vapor Pressure at Ambient Temperature: 0.85 atm
Ambient Saturation Concentration: 867,932 ppm or 86.8%

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
Wind: 10.7 meters/second from w at 3 meters
Ground Roughness: open country Cloud Cover: 5 tenths
Air Temperature: 15° C Stability Class: D
No Inversion Height Relative Humidity: 5%

SOURCE STRENGTH:
Direct Source: 2520 kilograms/min Source Height: 0
Release Duration: 60 minutes
Release Rate: 2,520 kilograms/min
Total Amount Released: 151,200 kilograms

THREAT ZONE:
Model Run: Gaussian
Red : 5.0 kilometers --- (44 ppm = AEGL-3 [60 min])
Orange: 7.8 kilometers --- (24 ppm = AEGL-2 [60 min])
Yellow: greater than 10 km --- (1 ppm = AEGL-1 [60 min])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greater than 1 ppm (AEGL-1 [60 min])
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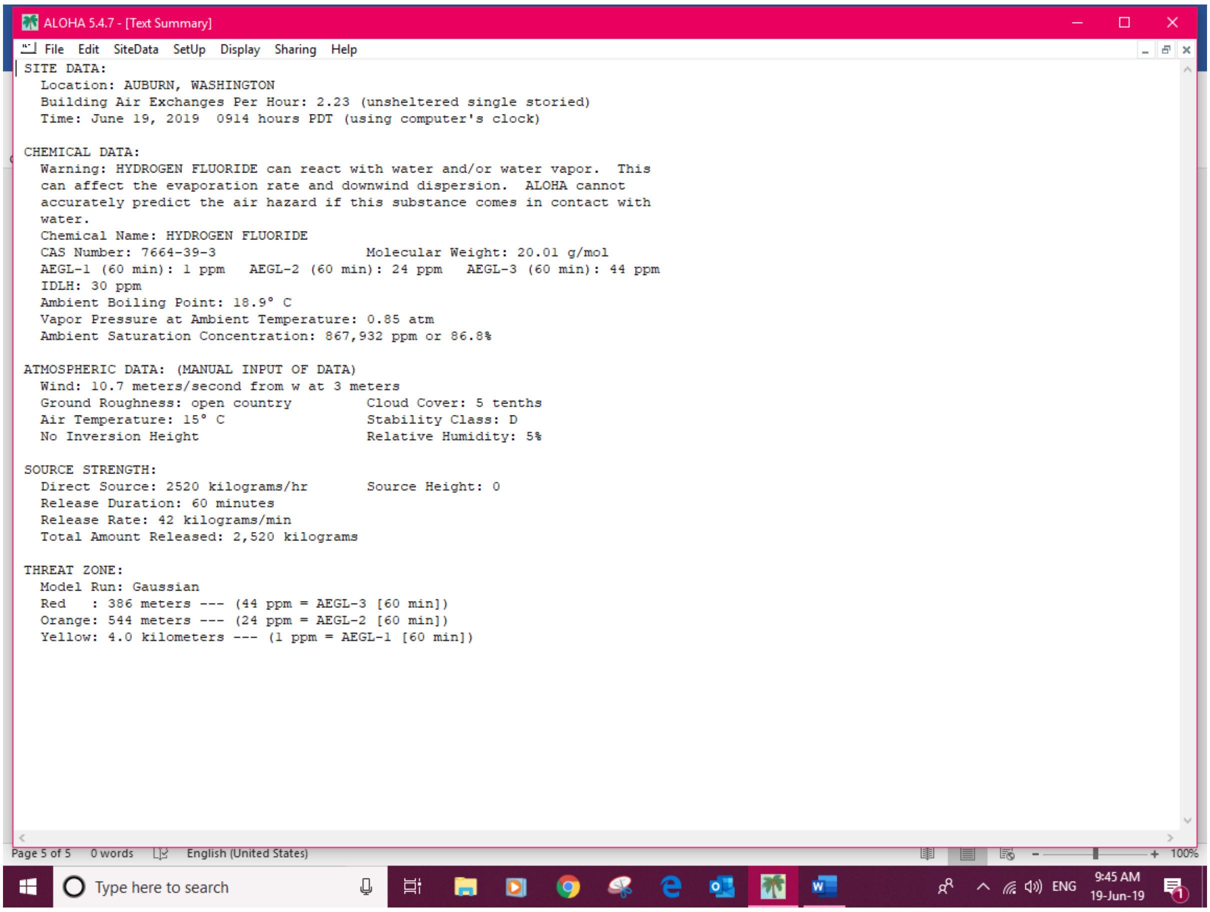

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  Time: June 19, 2019  0914 hours PDT (using computer's clock)

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  can affect the evaporation rate and downwind dispersion.  ALOHA cannot
  accurately predict the air hazard if this substance comes in contact with
  water.
  Chemical Name: HYDROGEN FLUORIDE
  CAS Number: 7664-39-3                  Molecular Weight: 20.01 g/mol
  AEGL-1 (60 min): 1 ppm   AEGL-2 (60 min): 24 ppm   AEGL-3 (60 min): 44 ppm
  IDLH: 30 ppm
  Ambient Boiling Point: 18.9° C
  Vapor Pressure at Ambient Temperature: 0.85 atm
  Ambient Saturation Concentration: 867,932 ppm or 86.8%

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
  Wind: 10.7 meters/second from w at 3 meters
  Ground Roughness: open country         Cloud Cover: 5 tenths
  Air Temperature: 15° C                 Stability Class: D
  No Inversion Height                    Relative Humidity: 5%

SOURCE STRENGTH:
  Direct Source: 2520 kilograms/hr       Source Height: 0
  Release Duration: 60 minutes
  Release Rate: 42 kilograms/min
  Total Amount Released: 2,520 kilograms

THREAT ZONE:
  Model Run: Gaussian
  Red   : 386 meters --- (44 ppm = AEGL-3 [60 min])
  Orange: 544 meters --- (24 ppm = AEGL-2 [60 min])
  Yellow: 4.0 kilometers --- (1 ppm = AEGL-1 [60 min])
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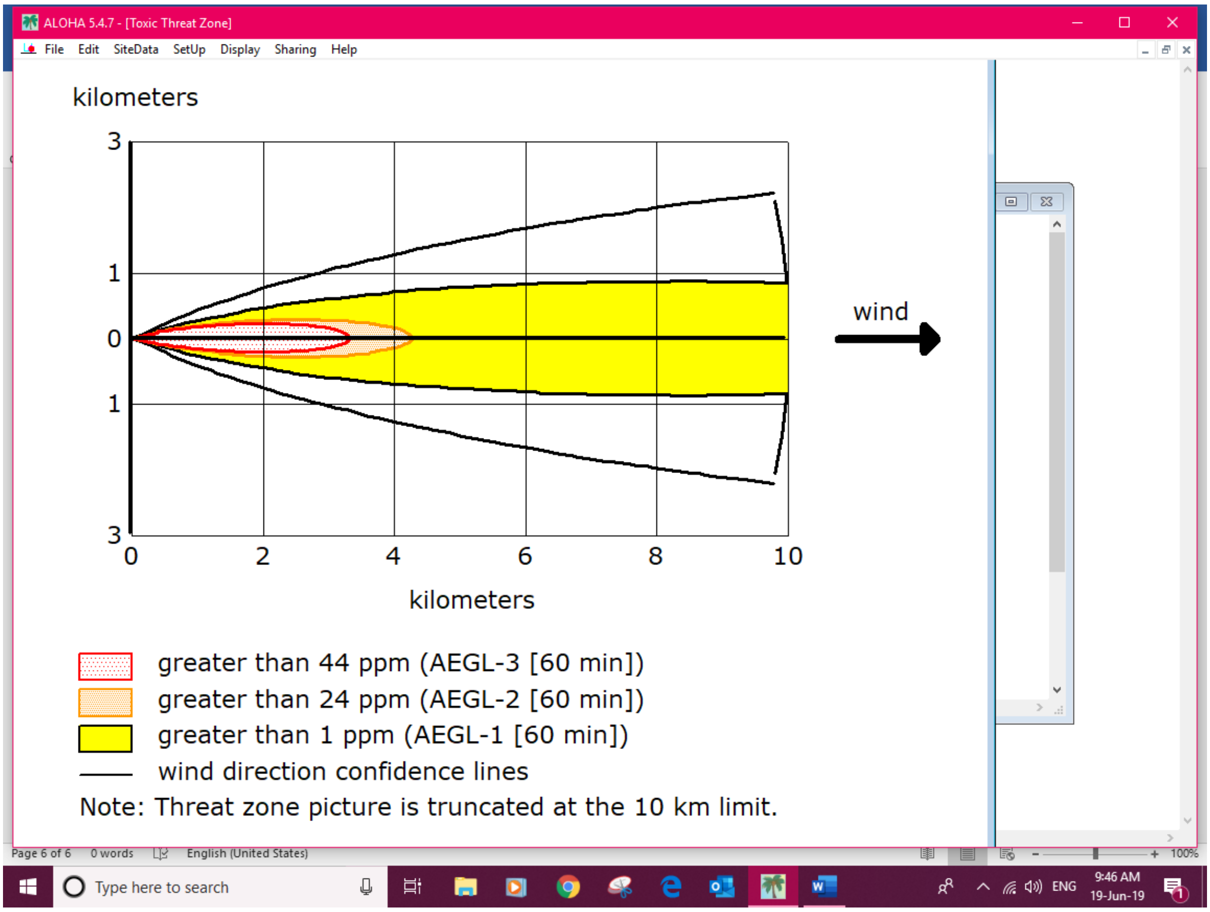
ALOHA 5.4.7 - [Toxic Threat Zone]
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kilometers
wind
greater than 44 ppm (AEGL-3 [60 min])
greater than 24 ppm (AEGL-2 [60 min])
greater than 1 ppm (AEGL-1 [60 min])
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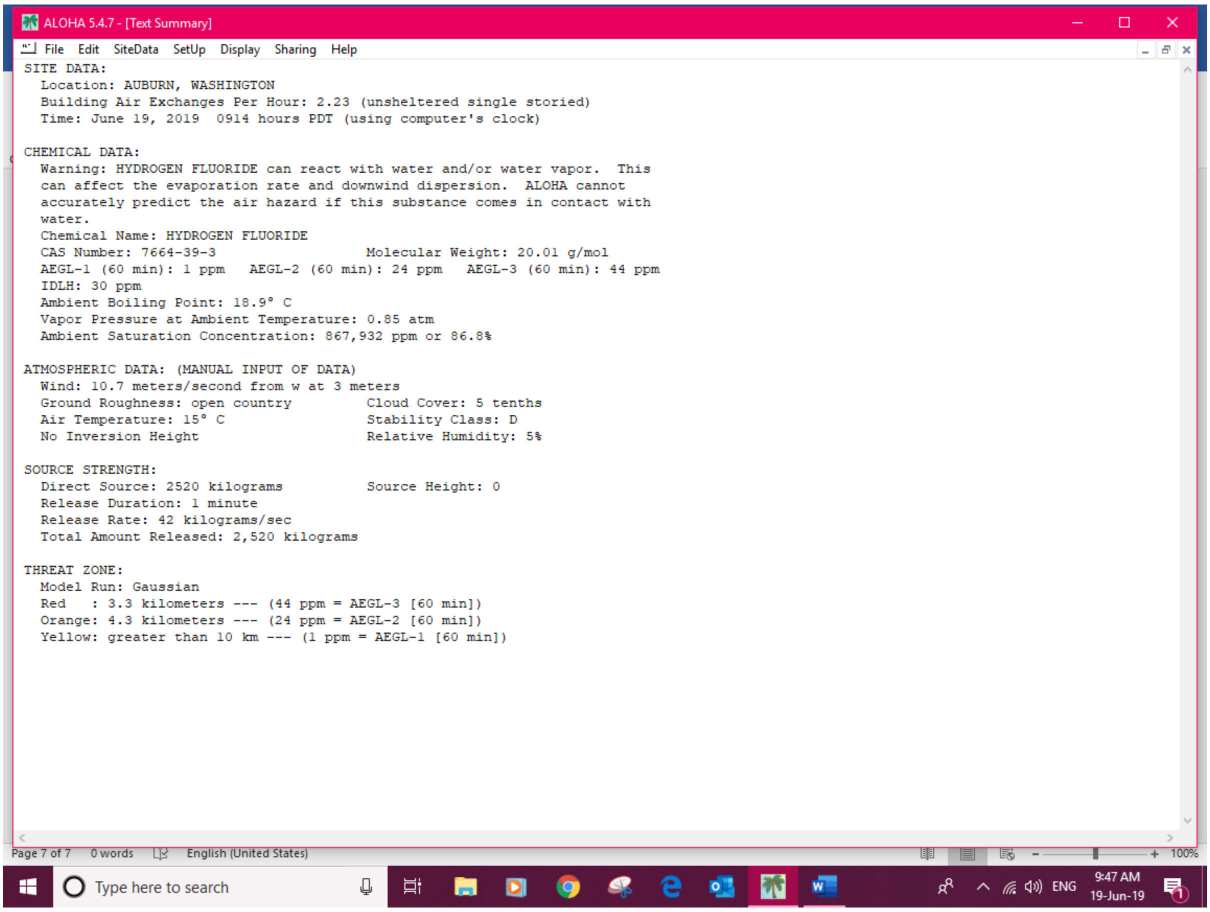


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CHEMICAL DATA:
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  water.
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  CAS Number: 7664-39-3                  Molecular Weight: 20.01 g/mol
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  IDLH: 30 ppm
  Ambient Boiling Point: 18.9° C
  Vapor Pressure at Ambient Temperature: 0.85 atm
  Ambient Saturation Concentration: 867,932 ppm or 86.8%

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
  Wind: 10.7 meters/second from w at 3 meters
  Ground Roughness: open country         Cloud Cover: 5 tenths
  Air Temperature: 15° C                 Stability Class: D
  No Inversion Height                    Relative Humidity: 5%

SOURCE STRENGTH:
  Direct Source: 2520 kilograms          Source Height: 0
  Release Duration: 1 minute
  Release Rate: 42 kilograms/sec
  Total Amount Released: 2,520 kilograms

THREAT ZONE:
  Model Run: Gaussian
  Red   : 3.3 kilometers --- (44 ppm = AEGL-3 [60 min])
  Orange: 4.3 kilometers --- (24 ppm = AEGL-2 [60 min])
  Yellow: greater than 10 km --- (1 ppm = AEGL-1 [60 min])
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APPENDIX B - FAVERSHAM NEWS ARTICLE DATED 15 AUGUST 2019

KM Faversham News

www.kentonline.co.uk/faversham TRUSTED NEWS SINCE 1884 kmfm 106fm Thursday, August 15, 2019 £1.50

PLUS KIDS' UNICORN COLOURING SETS TO BE WON SEE YOUR WHAT'S ON

Caroline Bunting has brought the initiative to Faversham

Hunt for hidden books

Primary school teacher Caroline Bunting is creating quite a stir by encouraging people to hide books for children.

Hundreds have already supported the initiative, which is designed to boost interest in reading.

■ See page 3

Gas fears if battery site burns

Fire at planned solar park could send toxic fumes for miles, warns expert

by Katie Davis
kdavis@thekmgroup.co.uk

An expert in biochemical engineering has warned toxic gas could spread for miles if a fire breaks out on what would be the UK's biggest solar park.

Dr Bruno Erasin says harmful hydrogen fluoride could spill into the air if a large blaze strikes a battery energy storage unit on the planned development on the outskirts of Faversham.

He is now urging government planning chiefs not to allow the battery site to be built within 15km of the nearest homes.

■ See page 7 for full story.

INSIDE

PROTECTION
Flood defences to be strengthened
PAGE 4

WHAT NOW?
Council to decide future of building
PAGE 5

'CREEPY'
Teacher jailed for sex with young girl
PAGE 6

With a 129MW capacity, this battery storage system in Australia is currently the world's biggest

Toxic gas fears if battery site goes up in flames

By Katie Davis
kdavis@thekmgroup.co.uk

A catastrophic fire at what would be the UK's biggest solar farm could see the air filled with toxic gas as far as six miles away, an expert in biochemical engineering has warned.

Dr Bruno Erasin says a blaze at a huge battery storage unit forming part of the planned development on the outskirts of Faversham would pose a "significant risk" to the surrounding population.

He has now urged government planning chiefs to order the solar park be built no closer than 15km from the nearest home.

Currently, a number of houses back onto the 1,200-acre site in Graveney, which would contain 880,000 solar panels and a number of battery units to store the energy they generate.

Dr Erasin says evidence shows a fire at the storage site - which covers 25 acres itself - could be explosive, difficult to control and send toxic hydrogen fluoride into the air.

Humans exposed to the toxic gas in high doses can suffer serious burns and serious damage to their respiratory systems.

With the exact size of the proposed Cleve Hill battery yet to be revealed, Dr Erasin has modelled his data on a 10,000kWh storage system.

In his report - based on hydrogen fluoride being released from a fire for an hour - he says concentrations in the air 4.5km away could be 2,444 times higher than derived domestic exposure limits.

Even 10km away, data modelling predicts readings 55 times higher.

Dr Erasin writes: "There are well-documented significant risks associated with large-scale energy storage units, including the risk of fire, and leaching of heavy metals into the environment during catastrophic events.

"In 2018 AIG Energy Industry Group reviewed lithium-ion battery energy storage systems and commented that 'battery fires are often very intense and difficult to control. They can take days and, or, even weeks to extinguish properly'.

"Based on this preliminary assessment using various scenarios and assumptions, it is concluded that the risk to human health in a catastrophic fire event of a 10,000kWh battery storage system is very significant and in my opinion not acceptable to potentially expose a large number of residents in the close vicinity of the proposed development at Cleve Hill Solar Park.

"The population both in the easterly direction of the development and westerly/south westerly direction of the development may be exposed to unacceptable risks including residents at Seasalter, Graveney, Faversham and Whitstable."

As well as the risks of a fire, Dr Erasin's report talks of the potential disastrous effects of severe flooding at the site.

In it he says there is the potential to release dangerous levels of copper and nickel into the water should the unit be submerged at 20 inches for between 12 and 24 hours, harming surrounding wildlife and fauna.

While developers plan to install a protective bund around the site, Dr Erasin says these have failed in previous cases.

He writes: "Based on this preliminary scenario, which would have to be further developed and verified, a preliminary conclusion can be drawn that the proposed battery storage systems at the Cleve Hill Solar Park could cause a foreseeable and significant environmental risk."

Lut Stewart, whose garden is just 10 metres away from the solar farm site, says Dr Erasin's findings are "extremely concerning".

"Of course we're worried," she said. "Given the concentrations 4.5km away, it would be catastrophic for those of us who live in the village.

"I have a small lithium battery in my mobility scooter which I'm not allowed to take on planes because it's deemed to be explosive, so I don't like to think of what could happen on a 25-acre site full of them. We'd have no hope."

Dr Erasin's report has been submitted to the Planning Inspectorate, which is considering the application for the solar park as part of a Development Consent Order, given its size and national significance.

Such a process removes planning powers from the local authority, with the Inspectorate instead making a recommendation to the energy secretary, Greg Clark, who will make a final decision.

Dr Erasin says the Inspectorate should not ignore the likelihood of catastrophic events such as fires and floods, given the 40-year operational period of the solar park.

The Faversham Society has also called for an Issue Specific Hearing to address concerns about the battery energy storage site.

■ What do you think? Email kentishgazette@thekmgroup.co.uk.

Concerned Lut Stewart lives near the site

'IT IS RIGHT TO BE SCRUTINISED'

Cleve Hill Solar Park Ltd says it is working on the battery storage plans with Swiss firm, Leclanché SA - a world leader in the industry.

A spokesman said: "Both the developers and the Swiss battery specialist put the safety of communities and their workforce at the heart of their designs and believe it is absolutely right to be scrutinised on the safety of the development.

"Cleve Hill Solar Park Ltd and Leclanché are designing an Outline Safety Management Plan which will be consulted on with the Kent Fire and Rescue Department and further assessed by the Planning Inspectorate as part of the ongoing examination for the scheme."

Daniel Föhr, vice-president of system enginerring at Leclanché, added: "As a battery system manufacturer with over 100 years' experience of providing high-quality energy storage solutions internationally, we design every solution to ensure we achieve the very highest levels of safety for both people and the wider environment."

APPENDIX C - EMISSIONS PARAMETERS SUPPLIED BY LECLANCHÉ SA

Substance	5 racks (kg) JH4
CO	374.55
H2	20.20
CO2	288.93
Methane	38.80
Ethylene	29.08
Ethane	10.39
Propylene	14.54
C4s	27.68
HF	2.07
Total	806.239

Substance	32 racks (kg)
CO	2397
H2	129
CO2	1849
Methane	248
Ethylene	186
Ethane	66
Propylene	93
C4s	177
HF	13

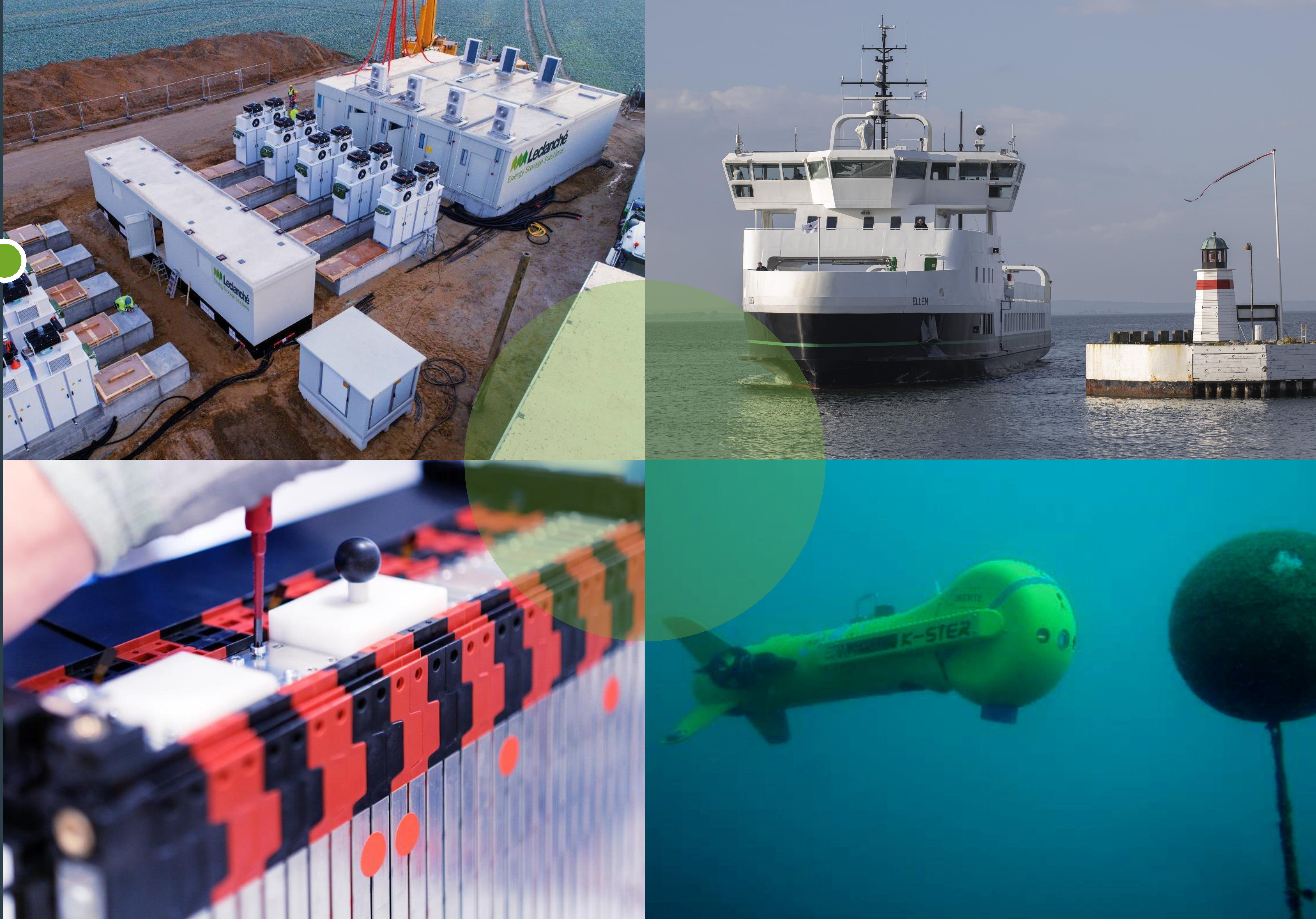
APPENDIX D – LECLANCHÉ CORPORATE PRESENTATION

Leclanché
Energy Storage Solutions

Corporate Presentation

Yverdon-les-Bains

August 2019



Agenda

Who we are

Leclanché technologies

Our reference customers

Our leadership team

Leclanché
Energy Storage Solutions

- STATIONNARY
- e-TRANSPORT
- SPECIALTY BATTERY
- LECLANCHE OFFICES

"We are a world leading provider of high quality energy storage solutions, accelerating the integration of renewable energy into our grids and powering the electrification of transport systems. We have over 100 years of battery and energy storage innovation, powered by German engineering and Swiss quality."

Leclanché
Energy Storage Solutions

What we do

Electrification of transport systems

We deliver integrated Battery Packs for Electric Vehicles of all sizes, with intelligent interface to the charging infrastructure.

Renewable energies integration

We deliver Energy Storage Systems that reliably add intermittent solar and wind energies in the electricity network as dispatchable power on an as needed basis.

World leading in-house technologies

Electrochemistry to Energy Management Software: Lithium Cells, Battery Modules, Racks & Packs; Battery Management System; Energy Management Software.

Our Value Proposition

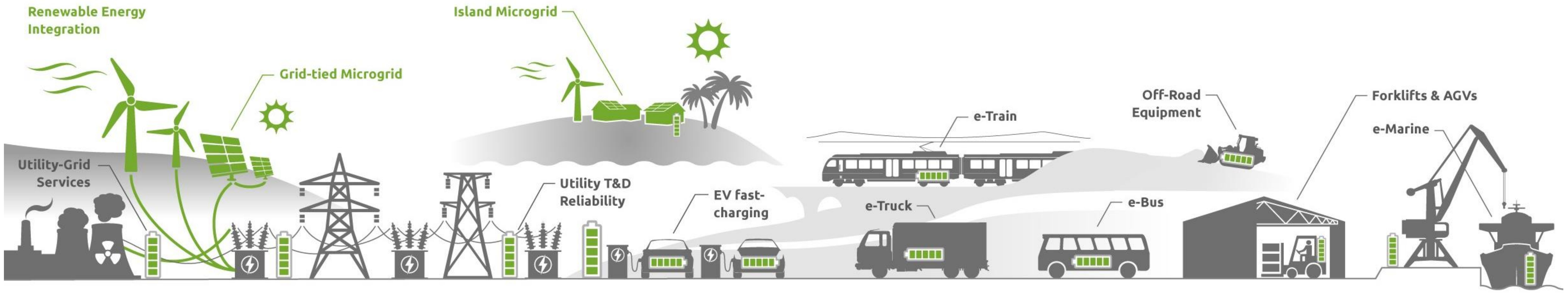
Energy Storage Solutions

STATIONARY SOLUTIONS

- Grid Ancillary Services
- Solar/Wind + Storage
- Microgrid Systems
- C&I Solutions
- Community Storage
- EV Charging Stations

e-TRANSPORT SOLUTIONS

- Electric Buses
- Electric Ferries
- Warehouse Equipment
- Industrial Marine Electrification/Hybridisation
- Fleet Trucks
- Rail & Off-highway



Analysis & Optimization

- System Modeling and Opportunity Analysis
- Project Optimization
- FEED

Flexible Sales Structure

- Turnkey EPC
- Supply & Commissioning
- PPA & Project Finance

System Control & Operation

- Multi-Application Energy Management System (EMS)
- System Degradation and Replenishment
- Remote Monitoring and Service

Total Integration

- Full process control: from in-house cell production to complete packs
- Infrastructure such as chargers and connectivity
- Fully integrated electric drive trains
- Homologation & Certification

System Engineering

- Scalable lithium-ion battery packs with thermal management
- State-of-art DNV-GL type approved battery racks for marine applications
- Battery packs engineered to operate faultlessly on majority of vehicles

Fleet Management

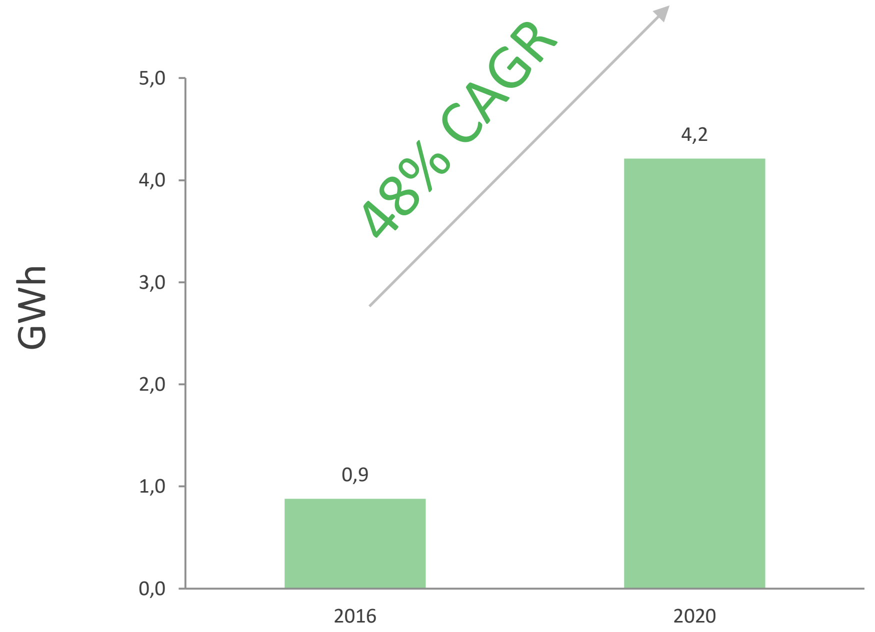
- Dynamic route simulation
- System planning
- Remote monitoring of all system components via a cloud service

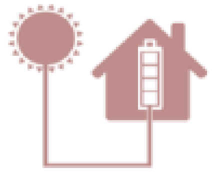
Leclanché
Energy Storage Solutions

We address USD10 billion market growing @37% CAGR

Utility-scale generation & microgrids

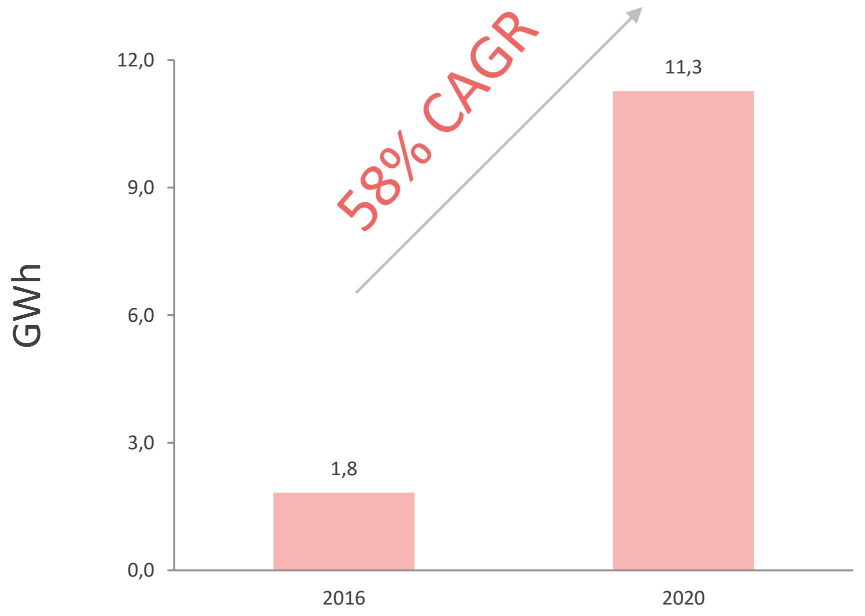
- Micro-grids: renewable integration
- Grid stabilisation and peak shifting
- Fast EV Charging

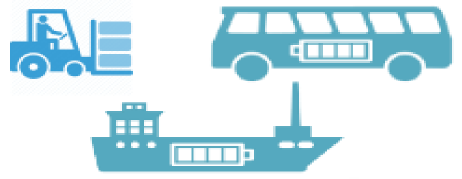




Commercial & industrial battery systems

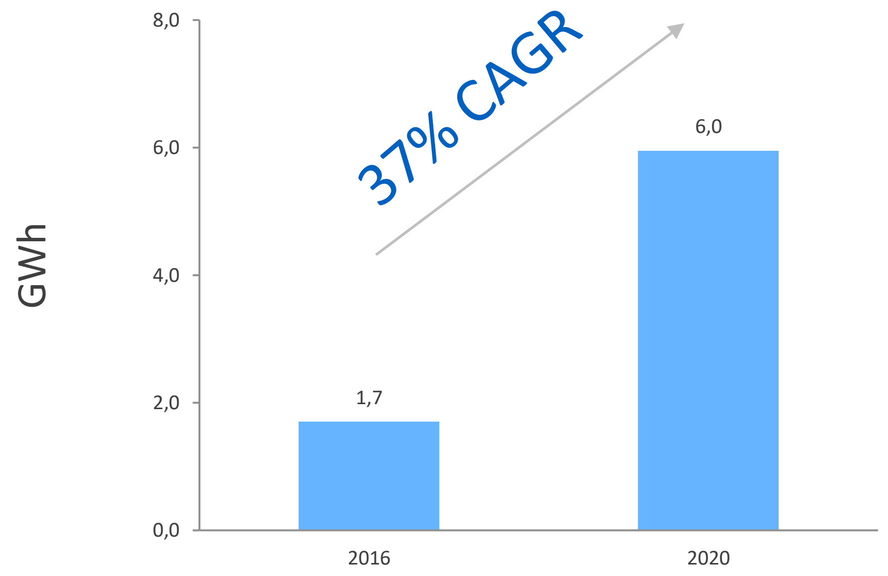
- Commercial, industrial & residential
- Solar lighting, medical, telecoms, security & defence
- Branded consumer (selected markets)





eTransport

- Fleets of buses, trains & trams
- Ferries and tugboats
- Forklifts, cranes, mining vehicles

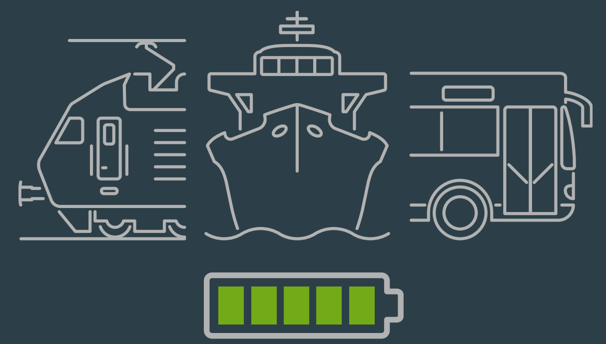


Source: Navigant Research

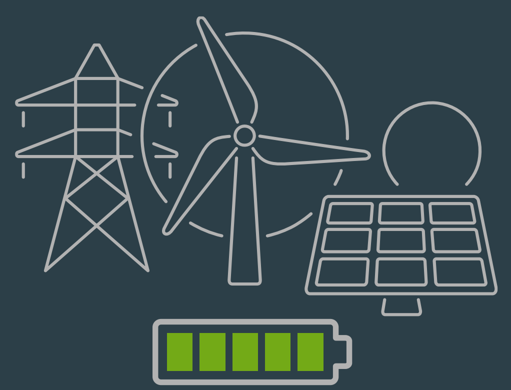
Leclanché
Energy Storage Solutions

World leading Leclanché energy storage technologies

Leclanché
Energy Storage Solutions



e-TRANSPORT SOLUTIONS



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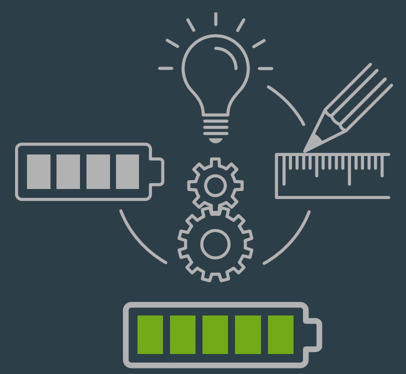


SPECIALTY BATTERY SYSTEMS

Our Technology

Lithium cells

- G/NMC cells for high energy density applications
- Titanate cells for high power, fast charge applications
- Industry leading cycle life, energy & power performance
- Automated production facility in Germany

Modules, Packs and Racks

Competitive custom design of Lithium cells, with in-house BMS, to design Battery Packs for a wide range of Electric Vehicles: *from eAuto rickshaw in India, to large eCargo vessel in Norway.*

Hybrid Battery Systems with fuel cells/ gas engines under development for long range vehicles.

Inhouse EMS-led Systems Integration for stationary storage solutions.

Advanced production techniques

WATERBASED Leclanché COATING

Battery chemistry technologies

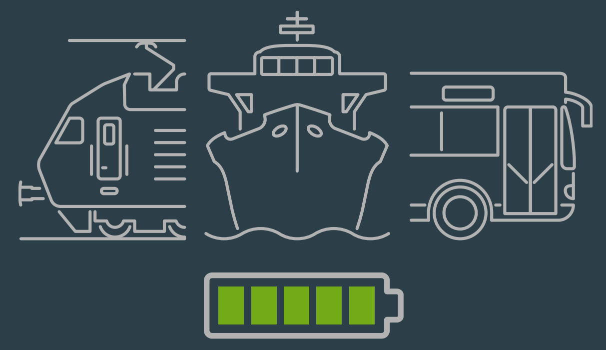
Proprietary Lithium Titanate Oxide (LTO) cells for leading performance in long-life and rapid-charge applications (sole manufacturer in Europe)

Proprietary G-NMC cells for energy intensive applications (continued R&D enhancements made)

Module design

Leclanché
Energy Storage Solutions

Common technology stack: serving multiple markets, enhancing margins



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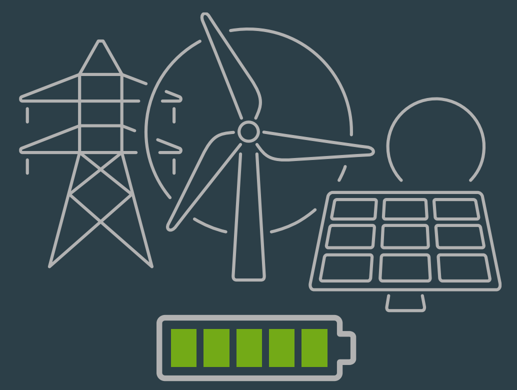

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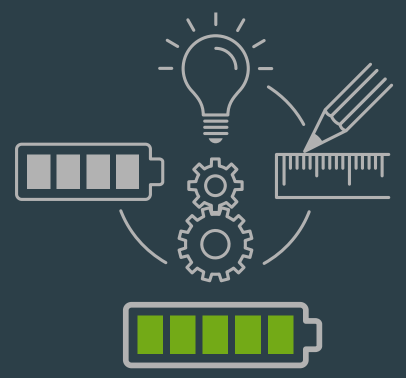


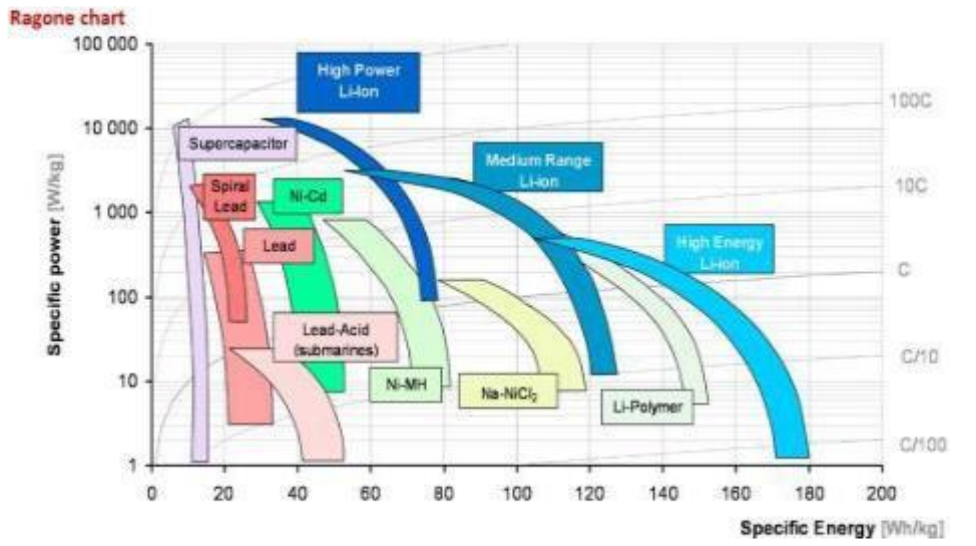
SPECIALTY BATTERY SYSTEMS

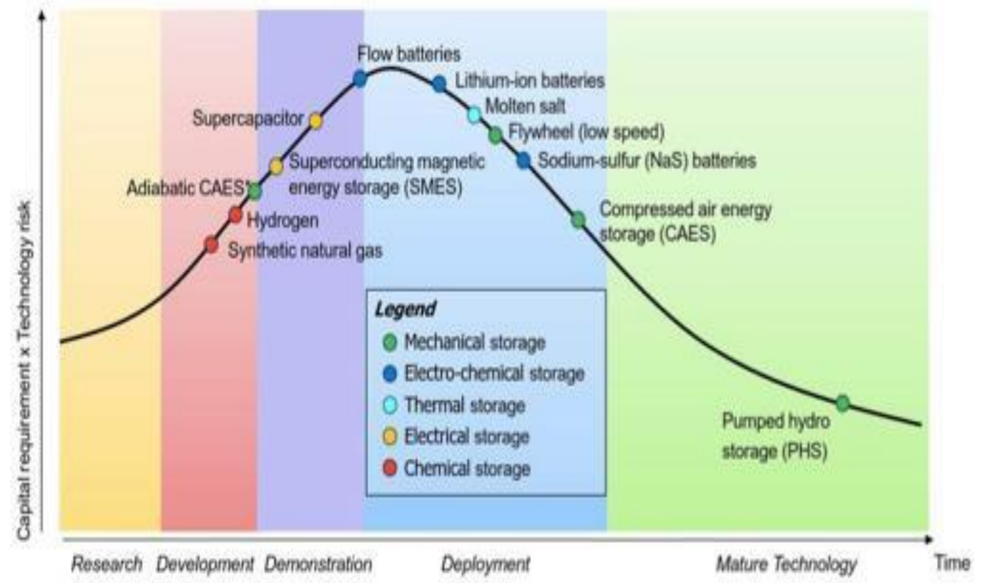
We deploy our proprietary cells, yet remain flexible to incorporate other storage technologies with our software and controls

	Lithium Titanate Oxide (LTO)	Lithium Graphite/NMC (G-NMC)
Cycle life	>20,000 @ 80% DoD	8,000 @ 80% DoD
Lifetime & warranty	Up to 20 years	Up to 10 years
Charge time to 90% SoC	Less than 15 minutes (4C)	1 hour (1C)
Charge acceptance	Symmetrical to discharge *(max. c-rate 7)*	Asymmetrical to discharge *(max. c-rate 1)*
Energy density	70 Wh / kg	210 Wh / kg within 2019 270 Wh/ kg in 2020
Temperature range	-20°C to +55°C	0°C to +45°C
Safety	Laminated ceramic separator	Laminated ceramic separator
Ideal use cases	•Power intensive applications •Long lasting applications •Applications needing rapid response •Grid stability projects	•Energy intensive Electric Vehicles •Renewable energy integration •Low cycle applications •Bulk storage or weight critical applications

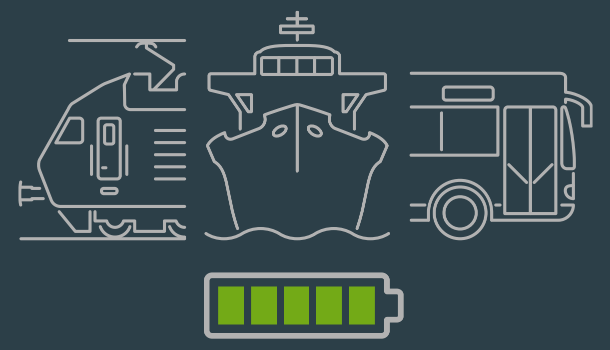
Integrated 3rd Party Technologies

- Hydrogen fuel cells
- NiMH
- Lead acid
- Ultracapacitors

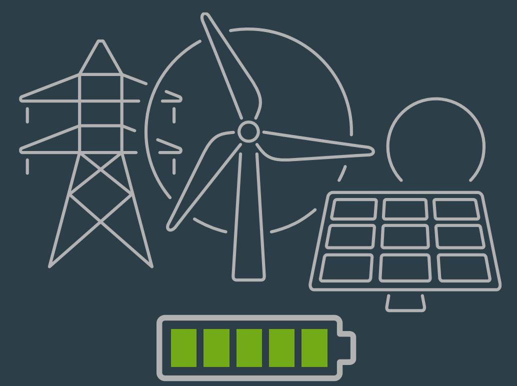




Leclanché
Energy Storage Solutions



e-TRANSPORT SOLUTIONS



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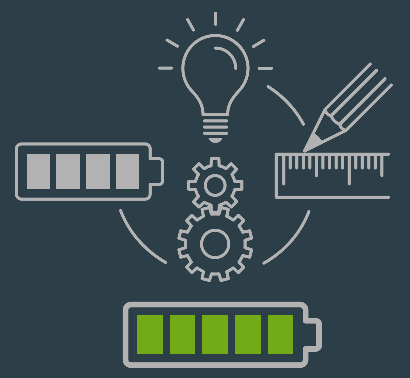


SPECIALTY BATTERY SYSTEMS

Our patents portfolio

Our IP portfolio of patents protects our proprietary cell technologies and water-based processing methods

Coverage area	# of patent families	# patents granted	# patents filed
LTO specific	5	35	5
Manufacturing process	3	37	30
Separator technology(1)	1	-	5
System/module integration	2	-	3
	11	**72**	**43**

Leclanché Energy Storage Solutions

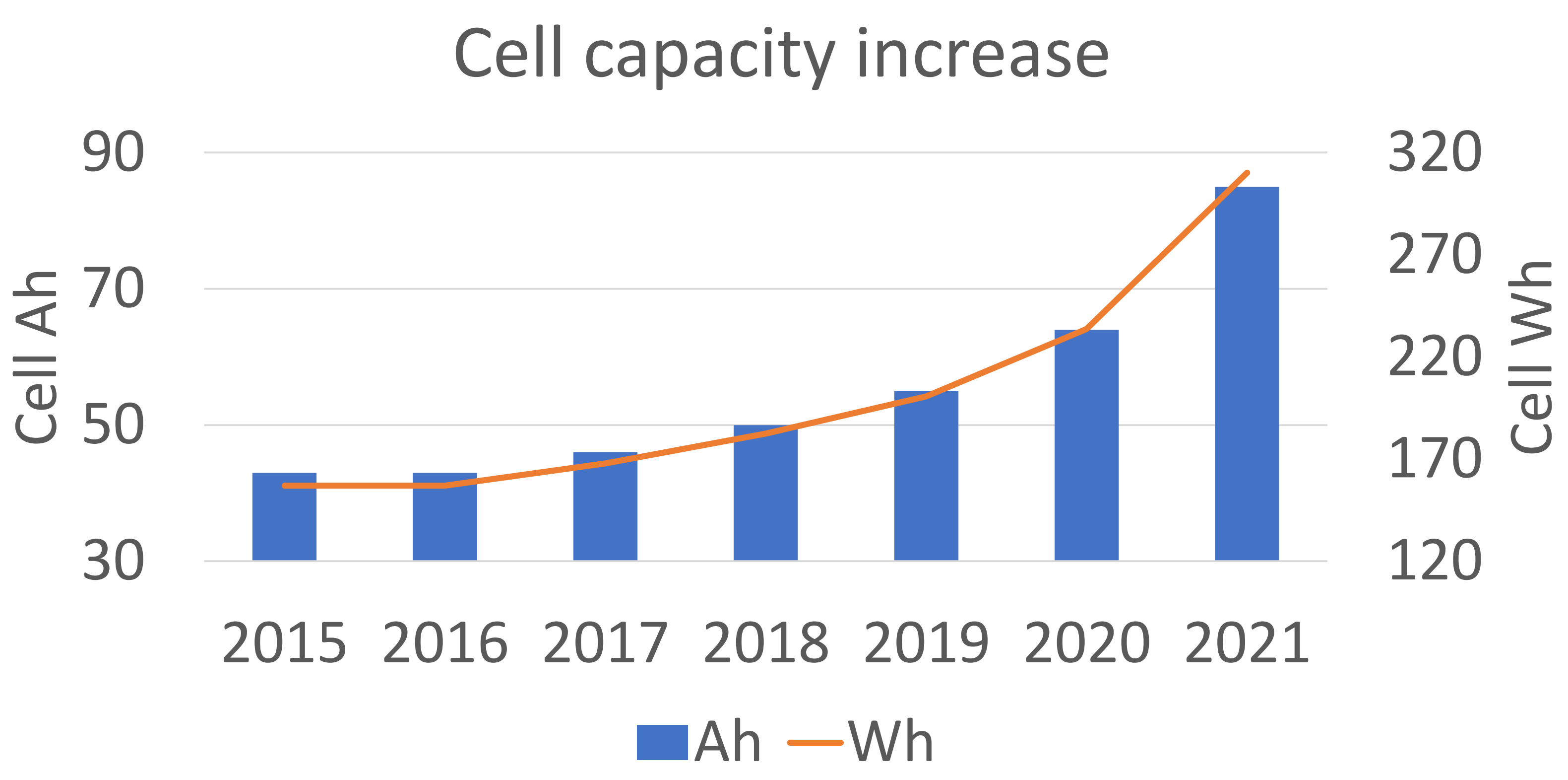
Competitive products: on target to achieve 55% cost reduction between 2015 and 2020 through innovation and engineering

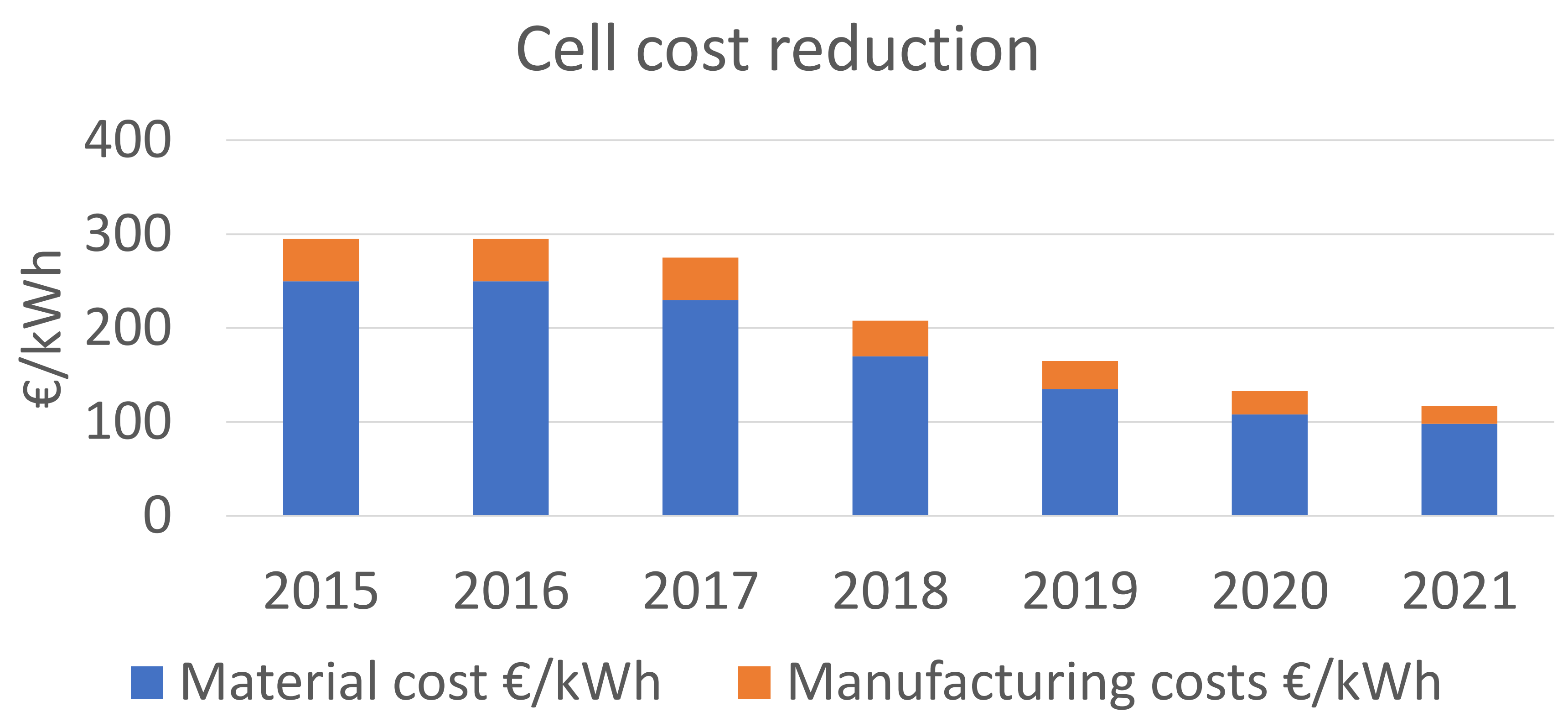
Reduced cost-base by more than 50%

Plans to triple cell manufacturing capacity

Systems Assembly and Testing capacity build-up

49% increase in Cell capacity; >90% for high energy density Cells





New modules for eTransport applications

- New gen M3 modules design: 30% reduction in component costs.
- New automated assembly line in Yverdon, Switzerland, by mid-2020 in partnership with Comau (Fiat Chrysler Automotive group company): > 5 fold increase, 350MWh in Module manufacturing capacity.

Continuous innovation: strong national and European alliances for lithium cells

EUR500 million initiative launched by the German Federal Ministry of Education and Research (BMBF)

Largest industrial partner within the consortium German funding budget of EUR1 billion

By 2020, Leclanché aims to deliver > 300Wh per kg/ 500 cycles cells for cars; >230Wh per Kg/ >2000 cycles cells for heavy duty transport vehicles

Battery cell research and production centre

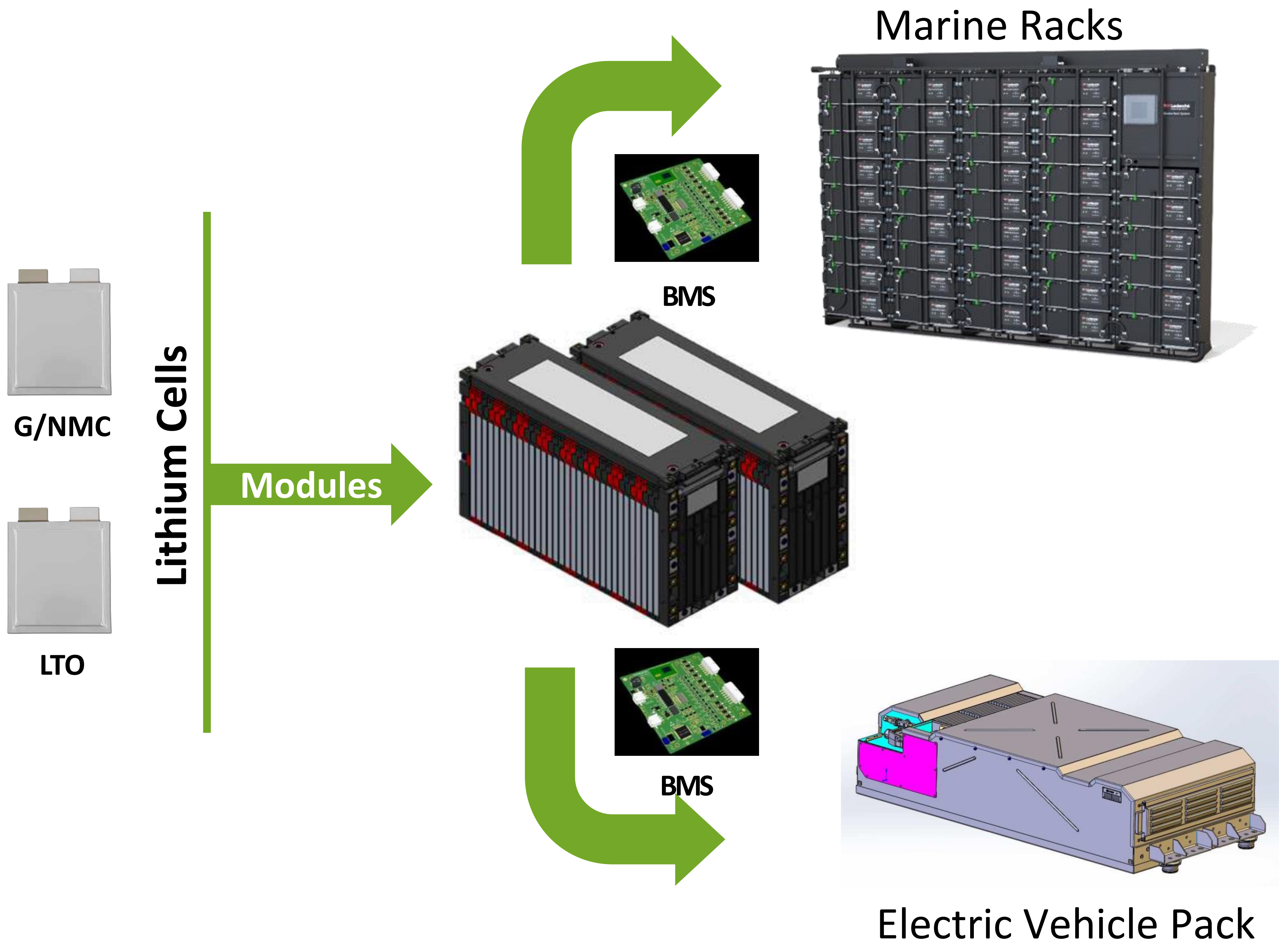
- Cell development plant for the battery industry, set-up through the Fraunhofer Institute, to produce cylindrical and pouch cells.
- Leclanché part of the industry consortium contributing to the plant set-up and operation.

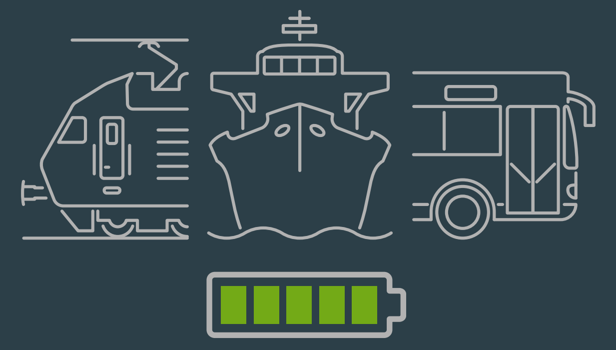
European Battery Alliance and "Batteriezellfertigung"

- Major cell production industrial ramp-up support from Germany through the EU's European Battery Alliance and the use of an IPCEI (Important Project of Common European Interest) process.
- Leclanché has notified its interest in participating in the process through the establishment of an industrial consortium led by Leclanché and other partners (Umicore, Solvay, SGL Carbon, CS Additive, Manz, PEC).

Leclanché integrated solutions for electrification of transport systems

- Superior in-house Cells and Battery Management Systems (BMS) to custom design Battery Packs for Electric Vehicles of all sizes.
- Intelligent and dynamically configurable integration with charging infrastructure to optimize fleet operations.

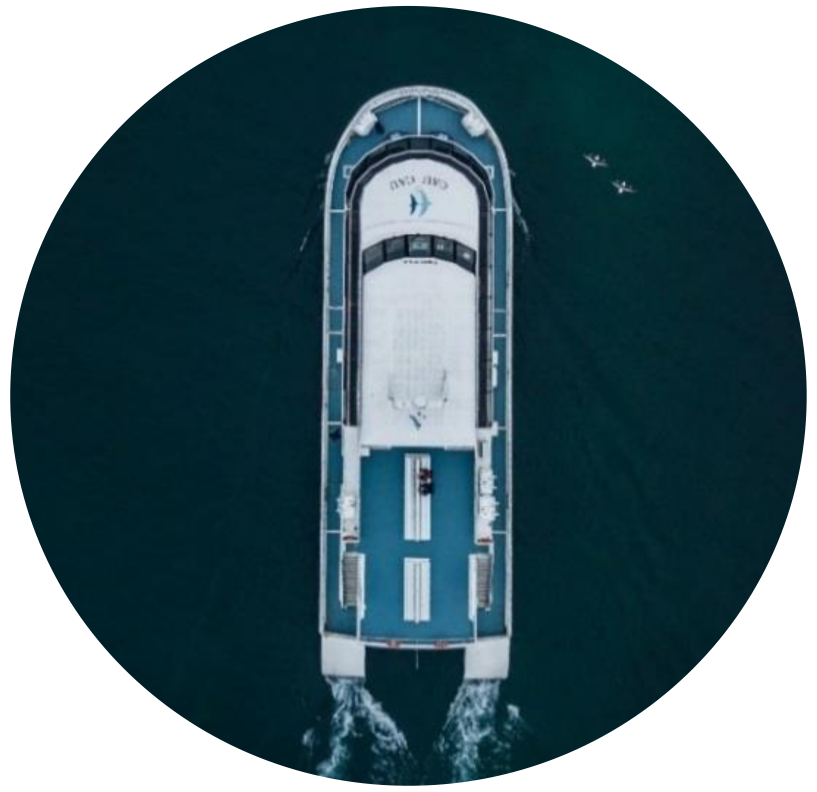




Transport systems application

Marine vessels

- Ferries
- Tugboats
- Containers



Land transport

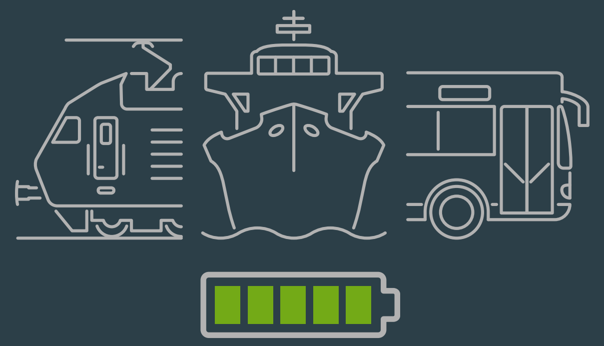
- Transit bus
- Trolley bus
- Light rail
- Heavy rail
- Rickshaws,
  2-3 wheelers

Off highway

- Cranes
- EME
- Mining

Material handling

- Forklift trucks



e-TRANSPORT SOLUTIONS

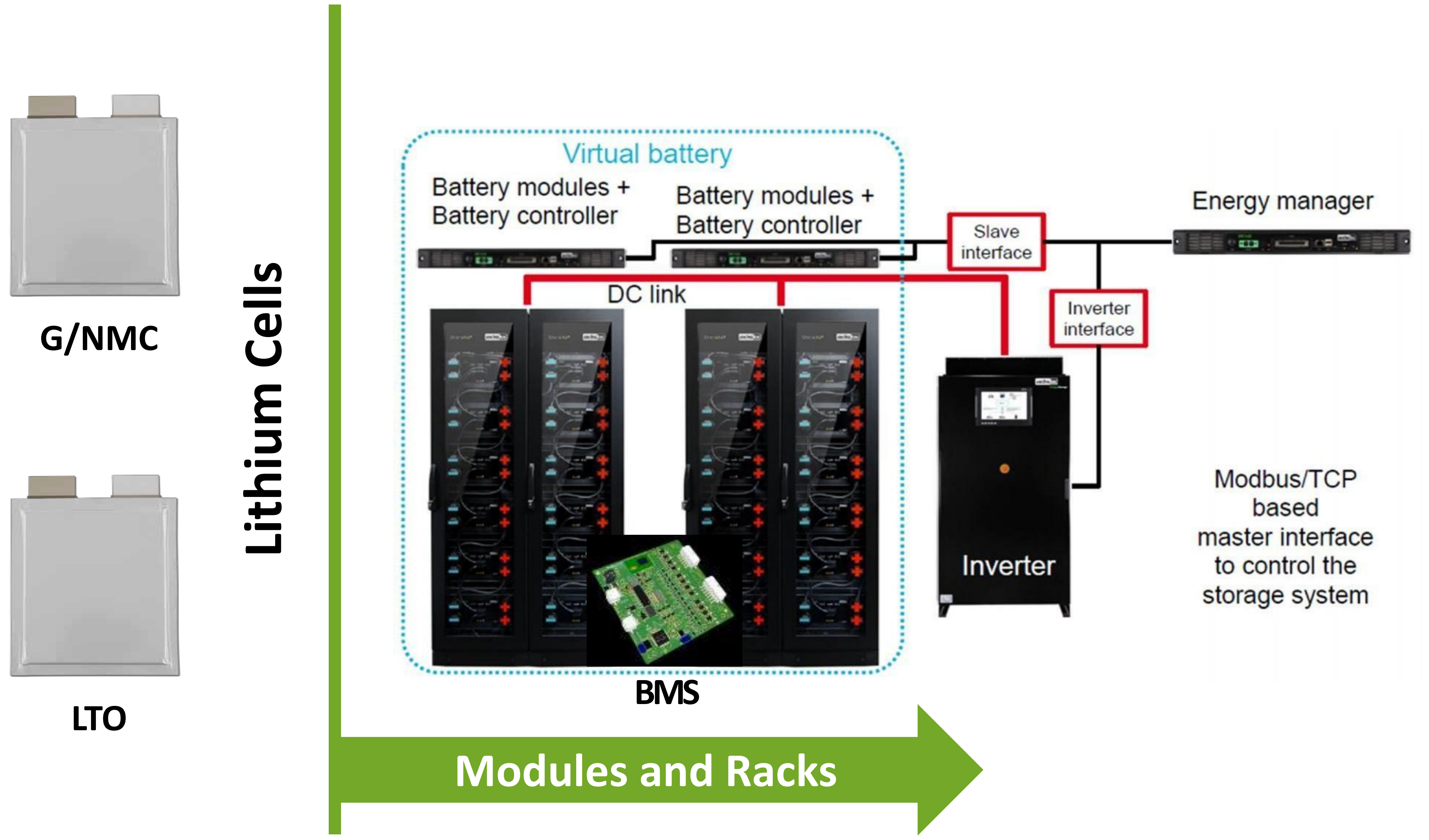
Leclanché
Energy Storage Solutions

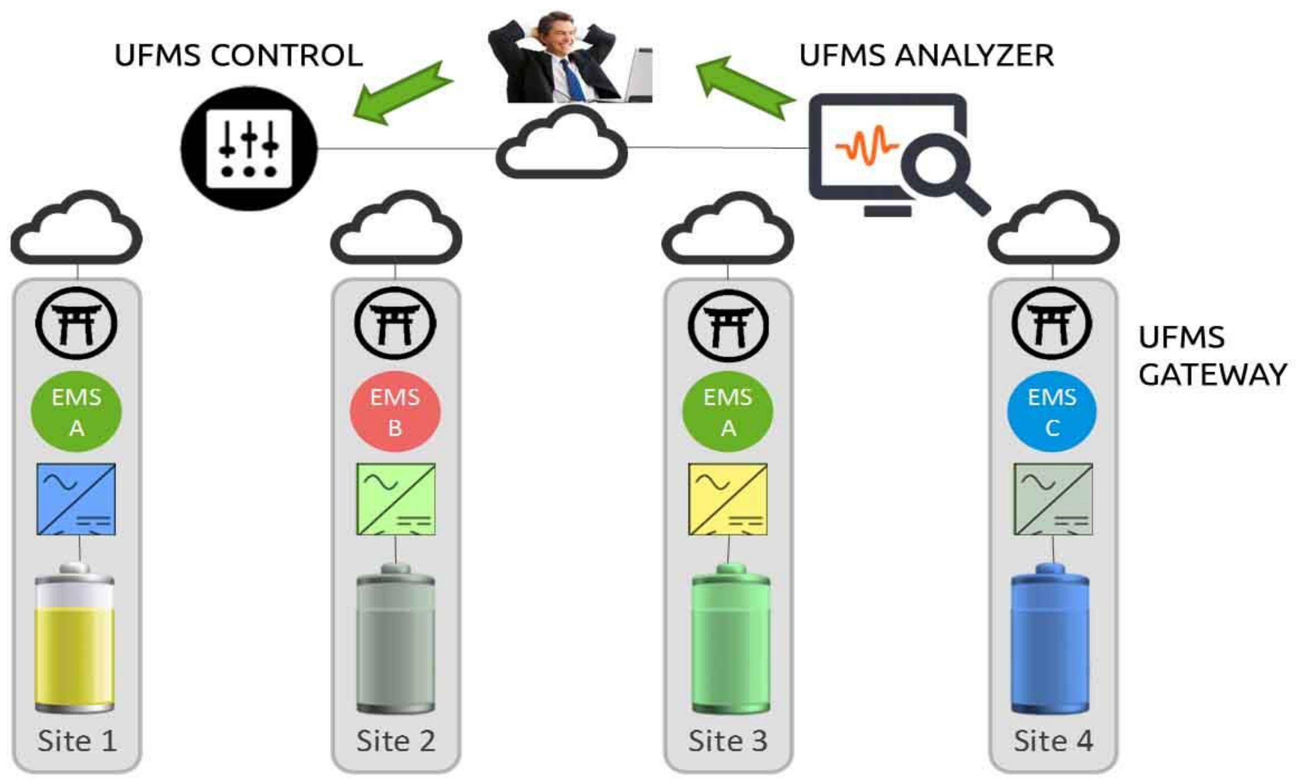
Leclanché energy storage systems for better integration of renewable energies

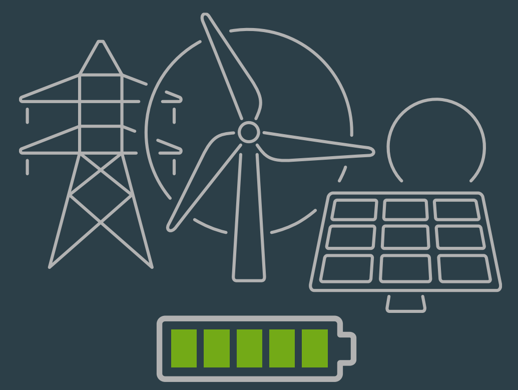
Leclanché Software and Controls package provides flexibility across multiple applications

Energy Management Software (EMS)

Universal Fleet Management Software (UFMS)







STATIONARY SOLUTIONS

Leclanché
Energy Storage Solutions

Customer applications delivered

C&I behind the meter

- Demand charge reduction
- Backup power/UP
- PV optimization

Utility services / grid Connected

- Ancillary services
- Transmission deferral

Microgrids

- Diesel displacement
- Renewables integration
- Grid stability

EV fast Charging

- Rapid DC EV charging

Solar PV related

- Solar ramp rate control
- Load shaping-shifting

Leclanché
Energy Storage Solutions

Our reference customers

Leclanché
Energy Storage Solutions

Stealing a march on our competitors in the fast growing Electric Vehicles (EV) market

Master Supply Agreements with recurring annual revenues

Custom-designed battery packs for fleets of Electric Vehicles based on 100% Leclanché technology

Energy storage solutions for smart charging infrastructure

We created a new business unit in the
fast growing EV market

Solutions developed and Engineered for Fleet EVs

We focused on the underserved e-Marine market

e-TRANSPORT SOLUTIONS

Yara Birkeland will be the world's first fully electric and autonomous container ship, with zero emissions. With this vessel, Yara will reduce diesel-powered truck haulage by 40,000 journeys a year.

Leclanché
Energy Storage Solutions

Stationary storage solutions for leading customers worldwide

From less than 1MWh in 2015 to 100MWh projects commissioned by 2018

Comprehensive set of software and controls for Leclanché Energy Management Software (EMS)

EPC turnkey solution for a wide range of applications

STATIONARY SOLUTIONS

EPFL
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Graciólica
CanadianSolar
enel Green Power
NRSTOR
ENERTRAG
S4 energy
swb
ieso
pjm
EXIDE

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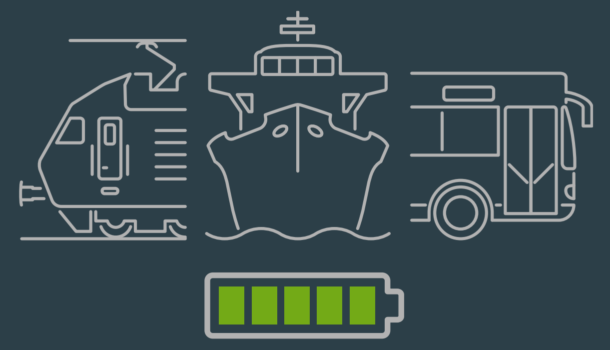
Energy Storage Solutions

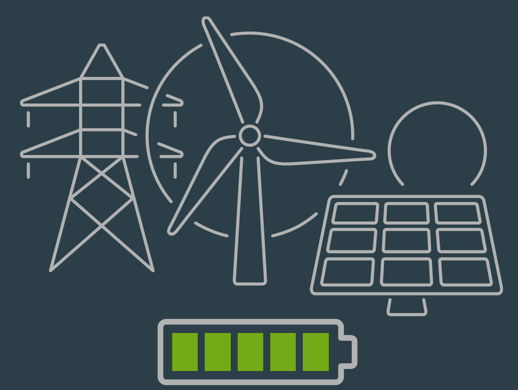
Our leadership team

Leclanché
Energy Storage Solutions

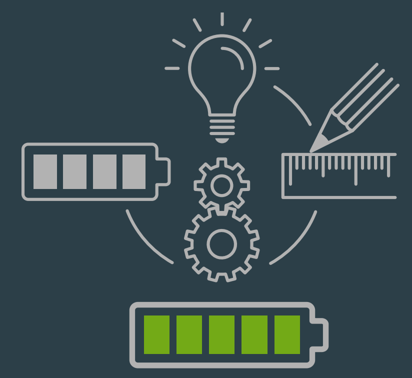
Our leadership team



e-TRANSPORT SOLUTIONS



STATIONARY SOLUTIONS



SPECIALTY BATTERY SYSTEMS

Anil Srivastava

CEO

Hubert Angleys

CFO & COO

Corporate Services

- Finance
- HR & Facilities
- Sales Operations
- Procurement
- Quality & EHSS
- Global Customer Services
- IT
- MarCom

Phil Broad

EVP

eTransport Solutions

- Sales
- Product Management
- Engineering
- Project Management
- Integration
- Homologation & Testing

Bryan Urban

EVP

Stationary Storage Solutions

- Sales
- Product Management
- EPC: Engineering, Procurement, Construction
- FEED, Project Finance
- EMS Development
- Project Management
- O&M

Fabrizio Marzolini

EVP

Specialty Battery Systems

- Sales
- Business Development
- Engineering
- Project Management

Pierre Blanc

CTIO

Product Delivery

- R&D Cells
- Module Technology Development
- BMS & Software Development
- Cells Production
- Modules & Battery Packs Production

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This presentation contains non-IFRS measures (including certain ratios and key performance indicators, such as MWh, or megawatt hour, which means a unit of energy equal to 1MW of power being applied continuously for one hour, which the Company uses to illustrate its overall production as demonstrated through the electrical energy storage capacity of its battery systems). These measures have limitations as analytical tools and should not be considered in isolation or as substitutes for analysis of the Company's results as reported under IFRS.

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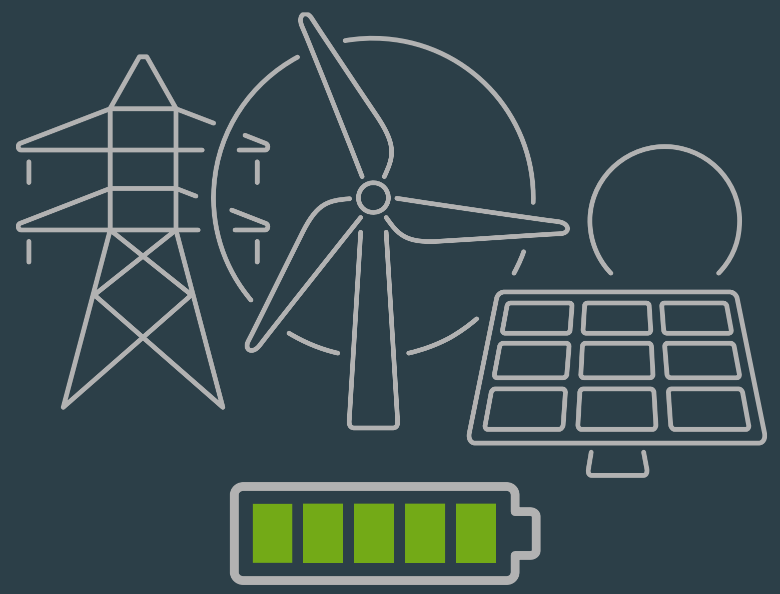
Leclanché

Energy Storage Solutions

Thank you



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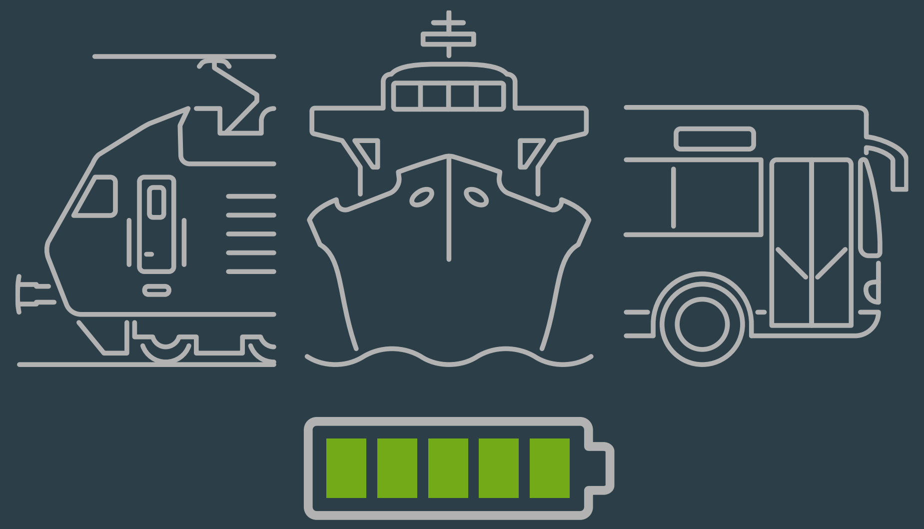
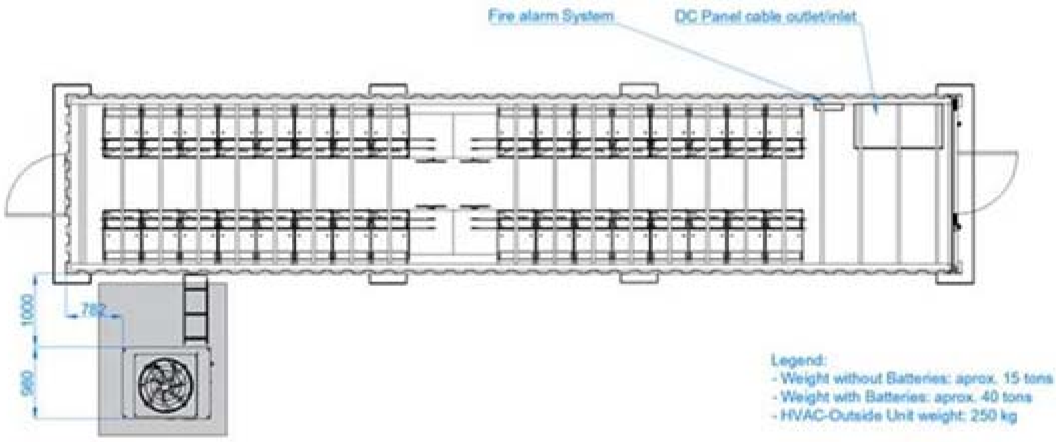


e-TRANSPORT SOLUTIONS

SPECIALTY BATTERY SYSTEMS

APPENDIX E – BATTERY RACK LAYOUT DIAGRAM



APPENDIX F – RECHARGE BATTERY EMISSIONS REPORT

Safety of lithium-ion batteries

RECHARGE

June 2013

The European Association for Advanced Rechargeable Batteries

Foreword

This publication is prepared to provide information regarding the subject matter covered. The document has been prepared with the information available at the time of its publication. It is communicated with the understanding that the authors are not engaged in rendering legal or other professional services on issues covered by this report.

Authors.

This publication has been prepared by RECHARGE aisbl.

The membership of **RECHARGE** includes suppliers of primary and secondary raw materials to the battery industry, rechargeable battery manufacturers, original equipment manufacturers, logistics partners and battery recyclers.

RECHARGE is following the continuously changing regulatory and legislative environment for rechargeable batteries and is a recognized expertise centre for advanced portable and industrial rechargeable battery technologies.

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B-1150 Brussels. Belgium.

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Content

1. Executive Summary

Lithium-ion battery safety has raised a large interest in the public in the recent years. This battery technology has been finding new markets since the years 2000. It is associated with the market development of cordless communication technologies and equipment such as cellular phones and portable computers, power tools and more recently tablets. In Europe it is the preferred battery technology for e-bikes, it is expected in the near future to be widely used in Plug-In Hybrid and full Electric Vehicles.

The number of rechargeable lithium-ion batteries used in cordless applications is well above one billion units per year and it is expected to grow in the mid-term. Despite the high safety standards used in the production of these batteries, several incidents have been reported, raising questions about the safety of this technology.

The aim of this document is to describe the risks associated with this technology, and how they are managed in order to guarantee a safe use of lithium-ion batteries. The following conclusions are drawn from this study.

1. **The safety protection is a fundamental function integrated in a lithium-ion battery**, minimizing the occurrence of the flammability hazard and its consequences by a combination of prevention, protection and mitigation systems:
   - **Prevention and protection** includes electronic protections, mechanical design and electric design incorporating the necessary redundancies to ensure the reliability of the safety protection: current and voltage control, state of charge and temperature management…
   - **Mitigation** systems reduce the consequences of defaults or abuse, e.g. internal shorts, temperature elevation, excess current, mechanical damage, through the usage of safety vents, heat protection or evacuation systems, mechanical protections…

2. **Product compliance with well established international or private standards** validate that the safety protection is adapted to the intended use. In addition, lithium-ion batteries have to be qualified for transport according to a UN safety standard, requiring manufacturers to comply with Safety Test requirements and a Quality Management System.

3. **The global approach to the hazard management has made the lithium-ion battery one of the safest energy storage systems**. Billions of electrical and electronic equipments powered by these batteries are used worldwide on a daily basis confirming that the safety of lithium-ion batteries is well managed.

4. **The major hazard offered by lithium-ion battery technologies is the evolution of a fire**, as a result of the flammability of the substances used in the battery.

A large majority of incidents reported recently found their origin in the following:

- Non-respect of UN provisions and packaging requirements prior to the transport of lithium-ion batteries.
- Cells assembly by non-professionals for innovative applications.
- Concentration of lithium-ion cells in non-controlled storage conditions or areas.

The lithium-ion battery Industry and RECHARGE are working at various levels of International and National Institutions to improve and guarantee the safety of lithium-ion batteries during use and transport while this battery technology is undergoing a strong market development.

2. Introduction

A lithium-ion battery is an electrochemical device optimized to store and release energy in the context of a specific application. All energy storage systems, whatever the system used, have a risk of unexpected environmental conditions or defaults which could create an accidental or uncontrolled energy release.

Specific environmental conditions are often used to test and characterize the stability of the energy storage system, defining the frontier between the acceptable conditions of use and the abusive conditions. In case of accidental abusive conditions or defaults producing some potential hazard occurrence, mitigations measures can be taken to avoid hazardous consequences. Using this information, products can be designed to control their safety with appropriate means both for the risk prevention and for the consequences mitigation while controlling any hazardous event during normal usage.

Table 1 below is describing some examples for different energy storage systems and the type of hazard they can offer. It appears that lithium-ion batteries have different behaviour compared to other battery technologies, requiring the use of suitable risk control and potential hazard mitigation, specifically relative to the so-called “thermal run-away” associated with a fire hazard. The aim of this document is to describe what are the risks associated with this technology, and how they are managed in order to guarante a safe use of lithium-ion batteries.

Energy storage technology	Potential hazard	Hazard Prevention	Potential hazard control
Water storage (hydraulic systems, dams,..)	Rupture, water flows	Avoid corrosion and mechanical rupture	Manage water streams
Liquid fuels (gasoline, diesel, ethanol,…)	Fire, explosion	Avoid sparks, flames	Manage fire and fume emissions
Lead acid and Alkaline Rechargeable batteries	Hydrogen gas release (mainly in overcharge), explosion, Acid and Alkali release	Avoid battery electrical abuse (e.g. voltage control and protection)	Manage gas flow release, neutralize spillage of acid or alkali,…
Lithium-ion batteries	Combustible gas release, corrosive electrolyte release, fire	Avoid heat or flames, and battery electrical abuse.	Manage fire and fumes emissions, neutralize spillage of electrolyte.

TABLE 1. Examples of different energy storage systems and the associated potential hazard.

3. Lithium-ion batteries: key features

3.1. Market and Applications

The lithium-ion battery technology is currently used in a large range of applications, both on the consumer, professional and industrial markets.

Portable-Rechargeable
- Electronic devices such as mobile phones, laptops and tablets
- Cordless Power Tools

E-Mobility
- Electric-Bikes
- Plug-In Hybrid Vehicles
- Electric Vehicles

Stationary
- Industrial Energy Power Stations
- Modular units for Grid Interface
- Supply of ancillary services to the electrical grid

Others
- Aeronautics
- Aerospace
- Military, Marine,…

Rechargeable lithium-ion batteries are primarily used in market segments where their high energy and power density as well as their superior cycling ability are requested.

As shown in Figure 1, prepared by AVICENNE, the future demand for lithium-ion batteries will be sustained in the portable market segment as well as in the E-mobility area.

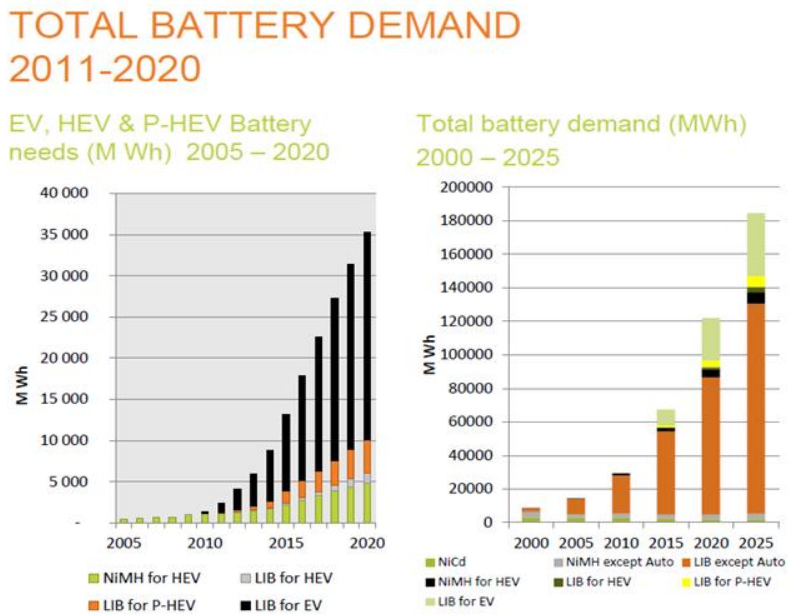


FIGURE 1. Evolution of the production for lithium-ion batteries by application.
(source: Christophe PILLOT. AVICENNE. 2012).

Lithium-ion batteries are the reference technology for plug-in and full-battery electric vehicles (PHEVs and BEVs) of the coming years. While other types of batteries, including lead-acid and nickel-metal hydride (in the first generation of the Toyota Prius hybrid) will continue to retain considerable market share in the short term, lithium-ion batteries are expected to dominate the market by 2017. Compared with other relevant battery types, lithium-ion batteries have the highest energy density as shown in Figure 2. Significant further improvements to the technology are expected in the coming years due to increases in the cell performance or via the battery engineering and design.

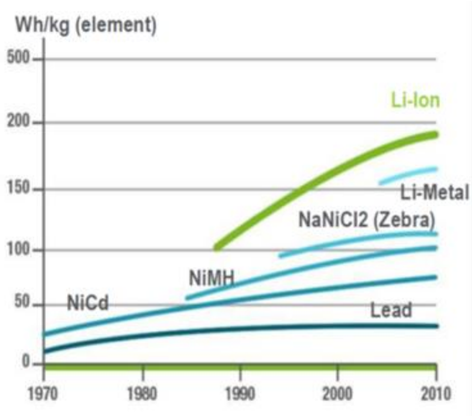


FIGURE 2. Energy Density Range for various battery technologies.
(Source. DAIMLER 2011)

In the future, there will be also high demand for these batteries in the energy storage sector.
Indeed, lithium-ion is also a technology of choice for large renewable energy farms in which smoothing functions are required along with ancillary services to the network (frequency regulation, primary power regulation), as both these requirements place a high demand on the battery cycling ability.

3.2. Chemistry and technology

3.2.1. A wide range of battery chemistries.

All lithium-ion technologies are based on the same principle: Lithium is stored in the anode (or negative electrode) and transported during the discharge to the cathode (or positive electrode) via an organic electrolyte. This principle is illustrated in Figure 3.

The most popular materials are graphite for the anode and a metal oxide for most of the cathode materials. The cathode material is based on Nickel, Manganese and Cobalt or made of iron phosphate. All of these materials have good lithium insertion or intercalation properties, allowing the storage of a large amount of electrical energy under a chemical form.

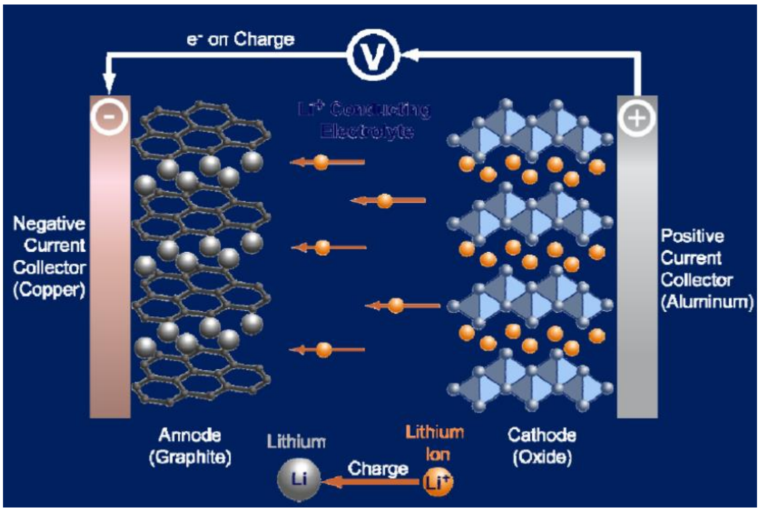


FIGURE 3. The basic operation principle of lithium-ion batteries.
(Source : Exponent 2011).

The selection of a battery technology depends on the application requirements regarding performance, life and cost, with each battery type providing specific functionalities. An illustration of the variety of properties offered by lithium-ion batteries is illustrated in TABLE 2 where the major components are detailed in a comparative presentation with the various battery technologies.

Name	LCO	LNO	NCA	NMC	LMO	LFP	LTO
Items	Lithium Cobalt Oxide	Lithium Nickel Oxide	Lithium Nickel Cobalt Aluminium Oxide	Lihium Nickel, Manganese Cobalt Oxide	Lithium Manganese Spinel	Lithium Iron Phosphate	Lithium Titanate
Cathode	LiCoO2	LiNiO2	Li(Ni0,85Co0,1 Al0,05)O2	Li(Ni0,33Mn0,3 3Co0,33)O2	LiMn2O4	LiFePO4	e.g.: LMO, NCA, …
Anode	Graphite	Graphite	Graphite	Graphite	Graphite	Graphite	Li4Ti5O12
Cell voltage	3,7 - 3,9V	3,6V	3,65V	3,8 - 4,0V	4,0V	3,3V	2,3 – 2,5V
Energy density	150mAh /g	150Wh/kg	130Wh/kg	170Wh/kg	120Wh/kg	130Wh/kg	85Wh/kg
Power	+	o	+	o	+	+	++
Safety	-	o	o	o	+	++	++
Lifetime	-	o	+	o	o	+	+++
Cost	--	+	o	o	+	+	o

TABLE 2. The major components of lithium-ion batteries and their properties.
(Source: Daimler analysis, Nationale Plattform Eletromobilität, 2010).

3.2.2. The different types of cell geometry.

Lithium-ion cells are manufactured in accordance with various types of cell formats and geometries. Some of them are illustrated in Figure 4.a. and 4.b.

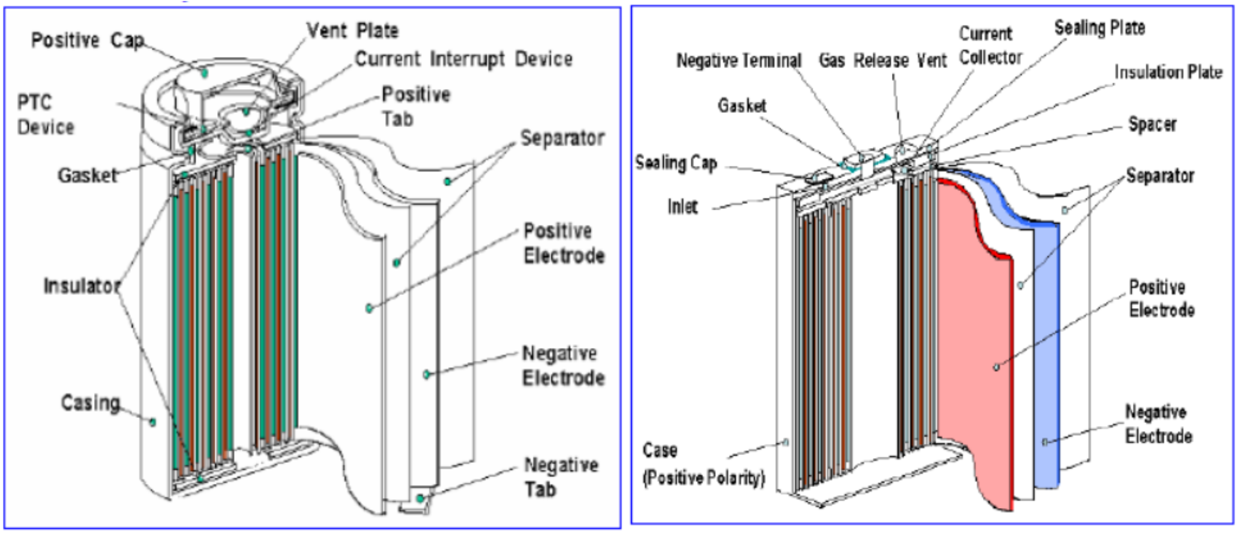


FIGURE 4.a. Various type of cell formats: cylindrical and prismatic lithium-ion battery

As illustrated in Figure 4a, hard case cylindrical or prismatic cells are produced: these cells are generally made of an aluminium can with laser-welded or crimped cover. They contain liquid electrolyte.

Soft case or « pouch cells » are also produced as shown in Figure 4b. These cells are using a thin aluminized plastic bag, glued with different type of polymers for the tightness. In general, they contain a gel or polymer electrolyte which justifies the qualification of "lithium-ion polymer" battery.

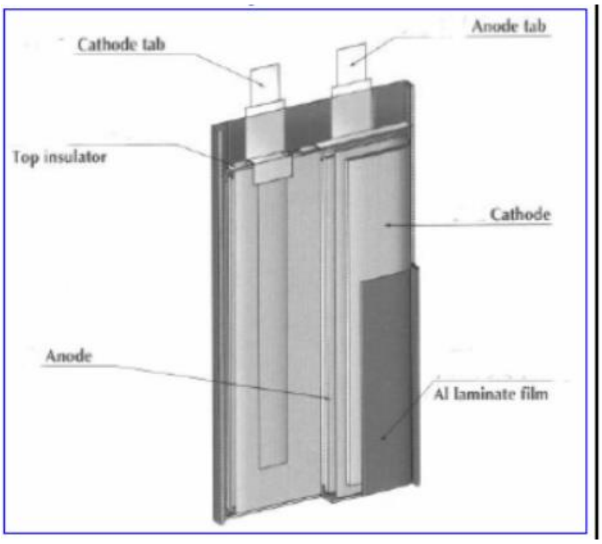
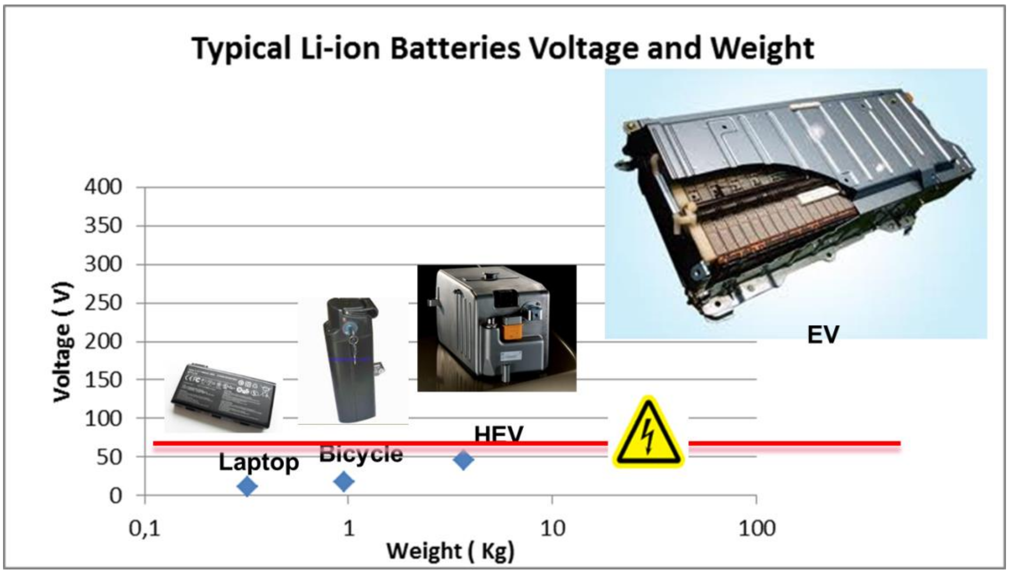


FIGURE 4.b. Various type of cell formats: The pouch cell of a lithium-ion Polymer battery

The cells are assembled to form battery packs and batteries, embedded in hard casing with electro-technical and electronic management systems (BMS). The final battery assembly (geometry and weight) and voltage is dependent of the cell type used and of their electrical assembly (series or parallel). The relation between battery weight and Voltage is illustrated in Figure 5 for several applications.



Source : Recharge

FIGURE 5. Evolution of the weight of the battery with the voltage of the application.

4 Lithium-ion battery hazards.

Safety assessment of a Lithium-ion battery requires the definition of the types of hazards they can offer, their occurrence probability and their consequences within the application.

4.1. The types of hazards.

As for any battery system, the Lithium-ion technology associates electrical risks and chemical risks. Depending on the environmental stress conditions, they can eventually create more or less dangerous consequences, called the potential hazards.

The potential hazards can be classified as below:

- The Chemical hazard
- The Electrical hazard
- Cumulative Electrical and Chemical hazards.
- High voltage (over 60 V-DC) hazard.
- Hazards due to loss of a function of the battery

4.1.1. The chemical hazard.

The substances contained inside the battery may present some chemicals risks. Although the battery is an article with no intended release of the substances during normal conditions of use, the case of accidental exposure has to be considered, in particular the rupture of casing due to mechanical damages, internal pressure, default,…. At this time, the following hazards may be observed.

- Spillage: hazard linked to the corrosive and flammable properties of the electrolyte.
- Gas Emission: hazard linked to the flammable properties of volatile organic substances.

The chemical risks associated with the direct exposure to the substances contained in the battery are exposed in the safety data sheet of the substances. A list of them is provided as an Annex to the Battery Information Factsheet prepared by RECHARGE (REF.1).

4.1.2. The Electrical Hazard.

Another type of hazard observed with all batteries is linked to the Electrical Energy content (according to the State of Charge).

The current flow through the battery in a conductive path is creating heat: this is known as the Joule effect. The heat generated by the electric current during charge /discharge processes is managed by a thermal management system.

In addition the battery has to be protected against high electrical currents and short circuits (internal, external or created by mechanical damage). Depending on the battery design, the heat created by these high currents may exceed the global battery cooling efficiency or create a local hot spot.

The state of charge needs to be controlled. The overcharge and over discharge generate unwanted reactions which are more exothermic than the normal one. They accelerate the temperature increase of the battery. In addition overcharge creates more chemical instability of some materials. This is the reason why electronic protection, generally based on voltage thresholds, is necessary for Lithium-ion batteries.

4.1.3. Cumulative effects (Chemical and Electrical).

In the case of energy storage systems like batteries, there is a potential cumulative effect of the chemical and the electrical hazards. In some specific circumstances it leads the so called “thermal run-away”. In case of a short-circuit, the Joule effect will increase the cell temperature to the point where the organic solvent leaves the cell via the vent. At this time any hot spot may induce a fire. The possible consequences of this cumulative effect are the following.

- Fire
- Toxic or harmful gas emission: CO, organic electrolyte,…
- Ejection of parts

The root causes of the thermal run-away are described in the parag 4.2.

4.1.4. High voltage (over 60 V-DC).

Large industrial or electric mobility batteries which are presenting a high voltage offer an additional hazard. Occupational Health recommendations fix a threshold at 60V for the electrical hazard of equipment in general and batteries in particular. In this case, the battery insulation loss may represent a direct danger to humans due to exposure to high voltage or high current: the usage of Lithium-ion batteries assembled to offer high voltage (over 60 V) has to respect the applicable electrical protection standards (terminals protection, insulation faults control to avoid exposure to dangerous battery voltage, etc…).

4.1.5. Loss of one (or more) of the battery service functions.

In many applications of industrial or mobility batteries, the control of the application relies on the battery power. A sudden loss of such a service function due to a battery failure can create a danger to the user. This hazard has to be analyzed in relation to each application.

4.2. Root causes of a thermal run-away.

It is important to understand the root causes of the potential hazards in order to define a specific and reliable risk management.

4.2.1. A materials issue.

The root cause of the thermal run-away is linked to the properties of the substances used in the battery. Indeed, Lithium-ion batteries contain several components which can under specific conditions react and generate heat or flames.

As shown in Table 3 below , the components used in a Lithium-ion cell are completely stable up to 80°C. At higher temperatures, the passivation layer called SEI (Solid–Electrolyte Interface : a thin layer of carbonated compounds passivating the surface of the graphite negative electrodes) starts a progressive dissolution in the electrolyte, becoming significant at 120-130°C. Due to this mechanism, the electrolyte further reacts with the least protected surface of graphite, generating some heat.

Temp (°C)	Reaction identified	Energy (J/g)	Comment
120-130	Passivation layer	200-350	Passive layer breaks Solubilisation starts below 100°C
130-140	PE separator melts	-90	Endothermic
160-170	PP separator melts	-190	Endothermic
200	Solvents-$LiPF_6$	300	Slow kinetic
240-250	LiC_6 + binder	300-500	
240-250	LiC_6 + electrolyte	1000-1500	
200-230	Positive material decomposition	1000	O_2 emission reacts with solvents

Values measured with differential scanning calorimetry on electrodes, may be partially representative of the reactions in the cell

TABLE 3. Thermal stability of components used in a Lithium-ion battery.
(SOURCE: Saft)

Depending on the choice of components, the reactions onset temperature and the total energy of possible reactions can change. A well-known example is the selection of the positive active material: materials such as Lithium Nickel oxide or Lithium Cobalt oxide can decompose at high temperature and generate heat, while on the contrary Lithium Iron phosphate will not.

In addition, the energy of a given reaction may vary with the state of charge: for example, a discharged graphite negative electrode will not react with the electrolyte.

4.2.1. The Thermal Run-away mechanism.

The consequences of the heat evolution depends on the environment of the cells:

When the cells are in an environment where heat can be evacuated, the reactions described in § 4.2.1. will stabilize and cells will progressively cool down. This corresponds for example to batteries with cooling systems, or small batteries evacuating the heat through their external casing.

In contrast, when the heat cannot be evacuated (such has in a confined environment, or even worse, in a heated environment), the battery temperature will increase, and will reach a status where new reactions can start, generating even more heat.

This mechanism is called the “thermal run-away”. As described in FIGURE 6 below, several reactions involving the separator, electrolyte and positive could be ignited with the temperature increase: consequently, the heating rate accelerates from less than a 1°C/minute to more than 100°C per minute.

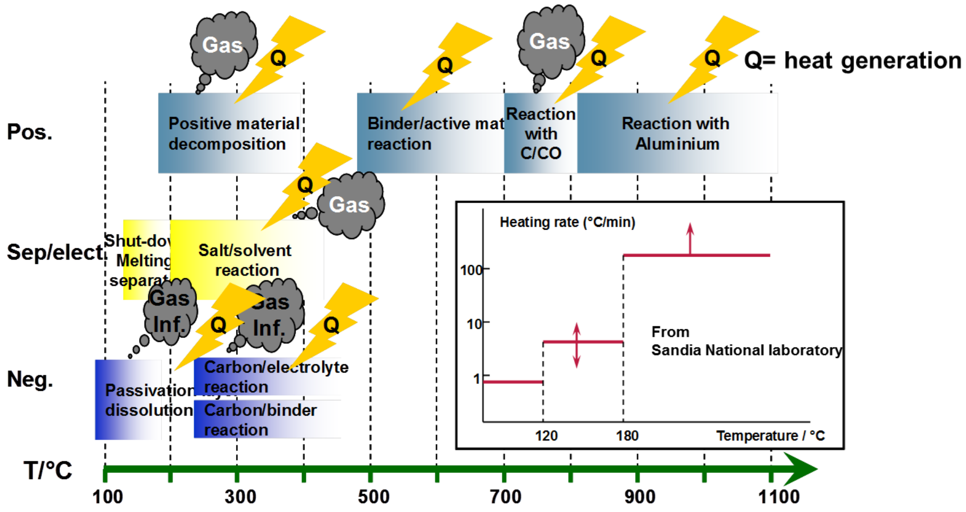


FIGURE 6. Schematic representation of conditions leading to a "Thermal Run-away"
(Source: Saft)

Without appropriate design to limit the run-away (such as venting, insulating layers,…), it can lead to a violent emission of gas and flames.

As explained above, the environmental reason creating the conditions of a thermal run-away can be the heat: this is the reason why it is recommended to protect Lithium-ion ion batteries from any heat sources.

The consequences of the thermal run-away are described in the next Chapter 4.3.

4.3. Hazard effects/consequences.

4.3.1. Gas emission during thermal run-away

During the run-away, several reactions occurr simultaneously. Their completion will depend on many factors:

- The heat and components generated by the competitive reactions,
- The state of charge,
- The size of the cells,
- The design of the cells (choice of the substances, efficiency of the protection components, etc..)
- The environment of the cells (efficiency of the cooling systems, local heat sources, atmosphere, etc…)
- Others.

Consequently, the information provided below on the consequences of a thermal run-away must be taken as general information. Each individual battery manufacturer should supply more accurate information on the consequences of a thermal run-away on its own battery systems.

The main consequences of the run-away are the emission of heat and gas which is flammable. The design of the cells and batteries generally integrates protections (like vents) in order to release gas without creating a risk of bursting the cells or batteries. In the same way, non-flammable plastics are used to avoid additional contribution of the plastic combustion to the heat generated. In TABLE 4, a list of gases emitted during the thermal run-away is supplied with indications of their relative concentration.

Molecule	Concentration (%)
CO	#40
H_2	# 30
CO_2	# 20
Methane	7
Ethylene	3
Ethane	1
Propylene	1
C4s and others	<1
Including HF	#0,3

TABLE 4. list of gases/substances emitted during the thermal run-away of a Lithium-ion battery
(SOURCE: Saft)

The emitted gas contains Carbon Monoxide (CO), Carbon Dioxide (CO2) and Hydrogen (H2) as well as traces of Hydrogen Fluoride (HF).

4.3.2. Gas combustion

Depending on the gas emission temperature and the contact conditions with air, the gas can self-ignite in air, adding the thermal energy of this additional combustion process to the thermal run-away.

The gas self-ignition and combustion will be avoided when,

- the temperature of the exhaust gas remains below 350 to 400°C,
- the gas or the ambient atmosphere are sufficiently diluted with an inert atmosphere (in order to reduce the Oxygen/Hydrogen ratio below the combustible mix limit of 4%).

On the contrary, the gas combustion will happen when,

- the gas temperature is over 350 to 400°C when it comes in contact with air.
- The gas temperature is lower, but the combustion starts due to an ignition in presence of air (by another flame, a spark or a hot point).

In case of combustion in air, the emitted gas may have the composition detailed in Table 5, below.

Molecule	Concentration (%)
N2 (min)	#65
CO	# 3
CO_2	# 27
Other combustion residues	# 5
Including HF	10-100 ppm

TABLE 5. Indicative composition of gases emitted during the self-ignition of components of a Lithium-ion battery
(SOURCE:Saft)

4.3.3. Heat generation during thermal run-away

Concerning the heat generation, the parameters used to characterize the severity of the event are the total heat release (in mega-Joules/kilogram of battery, MJ/kg) and the Heat Release Rate (HRR, in mega-Joules/battery surface unit, MJ/m2).

In case of run-away, the total heat release will depend of the reaction completion. In order to provide some quantitative information, the data presented below corresponds to the worst case scenario which includes gas combustion. These data have been measured on Lithium-ion batteries by several Institutions: INERIS, Sandia National Laboratory, Tiax and Saft (REFERENCE 2,3,4 and 5). According to these studies, large variations can be observed depending on the cell design and other parameters such as composition of the electrodes, type of casing, plastics contents, etc…and the testing conditions.
In FIGURE 7, a comparison is supplied between the heat release from a Lithium-ion Battery and other combustible materials. The analysis of this FIGURE confirms that the maximum heat release rate is very comparable between a Lithium-ion battery and gasoline while the total heat released is much lower for the battery. This is particularly illustrated in Figure 8 where the total combustion energy per unit battery (kg) is compared with the same parameter for gasoline.

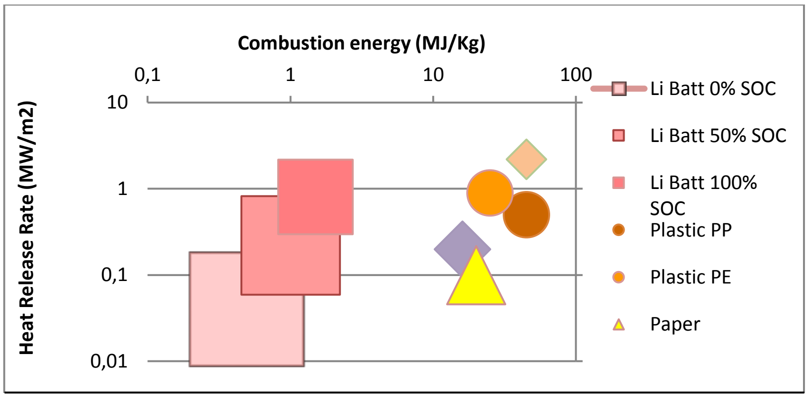
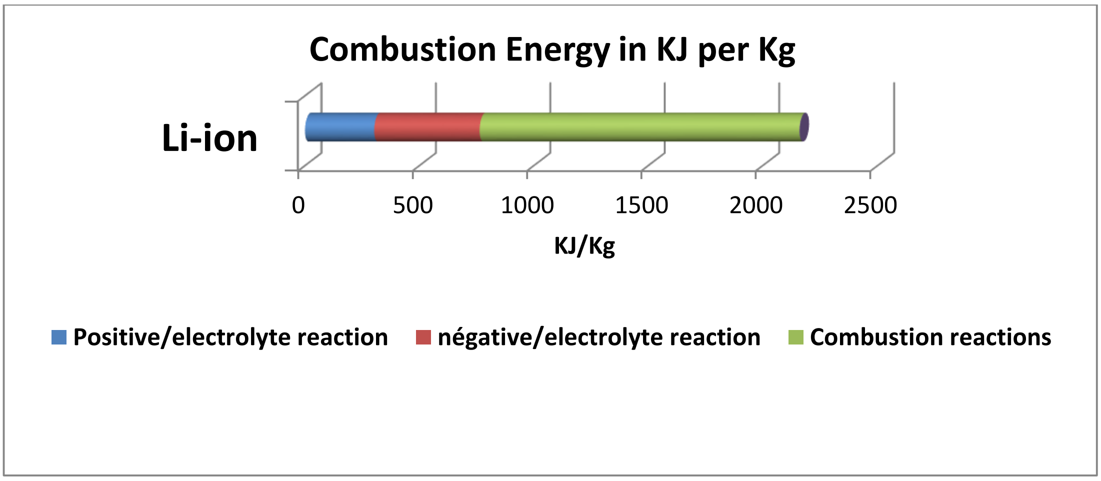


FIGURE 7. Correlation between the heat release rate and the combustion energy for various materials including the Lithium-ion battery. *(SOURCE: Recharge).*



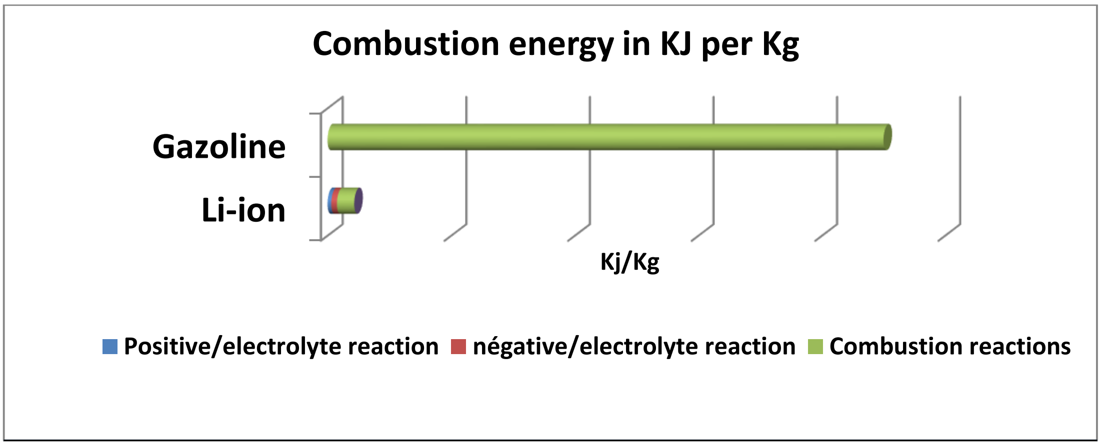


FIGURE 8. Comparison between the combustion energy of components of a Lithium-ion battery and gasoline. *(SOURCE: Recharge).*

This type of information is very useful to size the protections for mitigation of the run-away consequences. In the same way, the knowledge of the risk of fire and associated fumes allows the appropriate measures to be taken to manage the consequences without creating an uncontrolled event. This part is described in the paragraph 5 .

5. Lithium-ion battery safety management

5.1 Safety management approach

Potential hazards may not represent the same risk for the user, depending on the application: for example, fumes emissions may be considered as very dangerous in confined areas (car, houses, etc…) but not in remote open spaces (solar farms for example).

As illustrated in FIGURE 9 below, **Step 1** of the safety management approach starts with an analysis of the battery functions, and their interactions with the environment. This is called the "preliminary hazard analysis" and **"hazard identification".** At this stage, it is intended to cover all the aspects of the lifecycle: Design and qualification, Manufacturing, Transport, Use and End of Life. It results in a list of potential hazards for a given application, and the associated Safety Integration Level (SIL). The approach is coherent with the existing standard IEC 61508: "Functional safety of electrical/electronic/programmable electronic safety-related systems". In addition, the potential **failure mode** needs to be anticipated (**Step 2**).

The safety management will then consists in designing the product and the application in order to:

A: Prevent the potential hazards (Step 3): this phase is called the "Hazard source control", it consists of setting up protections against the failure risks and/or the environment stressing condition: the **prevention** measures.

B: Minimize the potential hazard and its consequences (Step 4): this phase is called the " hazard control". Concerning the battery system, the event consequences can be minimized through **mitigation**:

- reduce sensitivity
- reduce reaction
- break reaction chain

Limiting consequences of the potential hazard on the environment is also an important avenue: this has to be developed in coordination with the application, in order to set efficient **protection** measures.
The global approach is resumed on the following scheme:

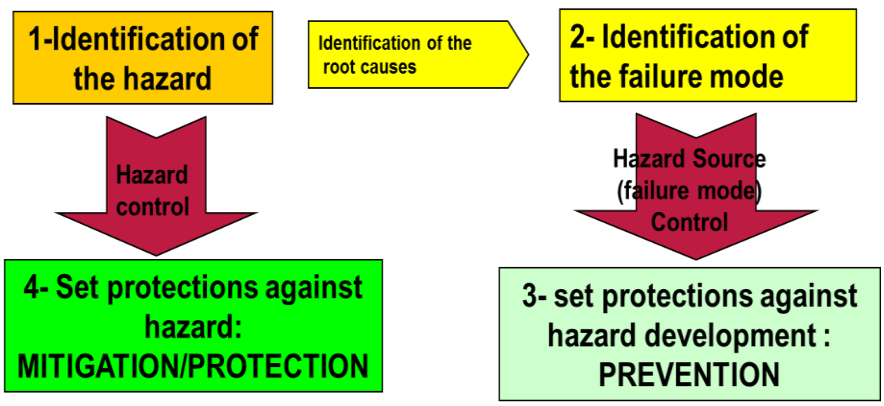


FIGURE 9. Schematic approach to Hazard identification and remediation.

5.2. Safety standards

EUCAR has developed a scale to define a level of danger for automotive applications. It is now widely used, as it helps describing the type of potential hazard observed with a Lithium-ion battery. The various hazard levels defined by EUCAR are described in the next Table.

Hazard Level	Description	Classification Criteria & Effect
0	No effect	No effect. No loss of functionality.
1	Passive protection activated	No defect; no leakage; no venting, fire, or flame; no rupture; no explosion; no exothermic reaction or thermal runaway. Cell reversibly damaged. Repair of protection device needed.
2	Defect/Damage	No leakage; no venting, fire, or flame; no rupture; no explosion; no exothermic reaction or thermal runaway. Cell irreversibly damaged. Repair needed.
3	Leakage Δ mass < 50%	No venting, fire, or flame*; no rupture; no explosion. Weight loss <50% of electrolyte weight (electrolyte = solvent + salt).
4	Venting Δ mass $\geq$ 50%	No fire or flame*; no rupture; no explosion. Weight loss $\geq$50% of electrolyte weight (electrolyte = solvent + salt).
5	Fire or Flame	No rupture; no explosion (*i.e.*, no flying parts).
6	Rupture	No explosion, but flying parts of the active mass.
7	Explosion	Explosion (*i.e.*, disintegration of the cell).

TABLE 6. Various hazard levels defined by EUCAR for the use of a battery in an Electric Vehicle.

In Table 6, level 4 is often considered as a "safe" behavior of the battery, particularly in the automotive application. Nevertheless, it should not be used as a general scale of hazards for other types of applications.

In general, there is a relationship between the level of event created by a battery and the severity of the environmental conditions. Logically, there is a threshold in all type of stresses (mechanical, thermal, electrical) above which the battery start reacting.

In order to specify the level and nature of stress, as well as the expected consequences, a large number of standards have been created either by international organism like UN, IEC or ISO or by private organizations.

These standards are based on two major types of tests.

- Some have as objective to test the battery's robustness limits: they focus on the nature and intensity of stress possibly creating a potential hazard on a Lithium-ion battery. By example, the temperature resistance test is often specified at 130°C to 150°C, with exposure times for 10 to 60 Minutes, because it is close to the limit where these exposure conditions may ignite the battery. These tests are often called "abusive tests".
- Other tests have the objective to validate the compatibility of the battery robustness with the application environment. Their focus is the test of the application stress on the battery: for example, vibrations tests simulating the expected vibrations during use in an automotive application.

Most of these standards also describe the expected tests results, with criteria defining the success of the test. This is intended to provide the safety guarantee for the considered application. International standards organizations have generated the following safety standards for Lithium-ion batteries (International Electrotechnical Commission (IEC) and International Organisation for Standardisation (ISO).

- IEC 62133-2 about safety requirement for portable battery cells.
- IEC 62660 about batteries for EV/HEV applications : 62660-1 : performances and 62660-2 : reliability.
- IEC 61427 about secondary cells and batteries for renewable energy storage
- ISO 12405 about test specifications for Lithium-ion traction battery packs and systems in Electric Vehicles

A series of requirements for each individual standard is described in Table 7.

	UN	IEC			ISO
Test Criteria Standard	Part II S38.3	IEC 62133	IEC 62281	IEC 62660-2	12405-1 12405-2
External short circuit	•	•	•	•	•
Abnormal charge	•	•	•	•	•
Forced discharge	•	•	•	•	•
Crush		•		•	
Impact	•		•		
Shock	•	•	•	•	•
Vibration	•	•	•	•	•
Heating		•		•	•
Temperature cycling	•	•	•	•	•
Low pressure (altitude)	•	•	•		
Projectile					
Drop		•	•		
Continuous low rate charging		•			
Molded casing heating test					
Open circuit voltage					
Insulation resistance					
Reverse charge					
Penetration					
Internal short cicuit		•			
Immersion					
Fire					

Source Saft

TABLE 7. List of tests requirements for each individual standard

Almost all of the IEC standards have been transposed into EN standards by CEN/CENELEC, the European standardisation body.

In addition, several groups of interest or private labels have created safety standards for Lithium-ion batteries. These are listed in Table 8.

	UL					NEMA	SAE	IEEE		BATSO	Telcordia	JIS	INERIS
Test Criteria Standard	UL 1642	UL2054	UL Subject 2271	UL Subject 2580	UL2575	C18.2M	J2464	IEEE 1625	IEEE 1725	BATSO 01	GR-3150	JIS C8714	ELLICERT D
External short circuit	•	•	•	•	•	•	•	•	•	•	•	•	•
Abnormal charge	•	•	•	•	•	•	•	•	•	•	•	•	•
Forced discharge	•	•	•	•	•	•	•	•	•		•	•	•
Crush	•	•	•	•	•	•	•	•	•	•	•	•	•
Impact	•	•	•	•		•		•	•				
Shock	•	•	•	•	•	•	•	•	•	•	•	•	•
Vibration	•	•	•	•	•	•	•	•	•	•	•	•	•
Heating	•	•	•	•	•	•	•	•	•			•	•
Temperature cycling	•	•	•	•	•	•	•	•	•	•		•	•
Low pressure (altitude)	•		•	•	•	•		•	•	•		•	•
Projectile	•	•	•	•				•	•				
Drop			•	•		•				•		•	•
Continuous low rate charging												•	
Molded casing heating test						•							
Open circuit voltage						•							
Insulation resistance				•		•							
Reverse charge			•	•									
Penetration			•	•			•						•
Internal short cicuit	•			•								•	
Immersion													•
Fire											•		•

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TABLE 8. List of tests requirements for individual standard

As indicated in Table 8, the types of abuse tests are very similar in most of the standards. The advantage is that the main usual safety risks of a Lithium-ion battery are checked in all standards, thus providing a protection to the user.

These standards may have some limitations.

- From the point of view of the application: the user must take care that the standard selected covers correctly the hazard in his own application (some application specific aspects may escape a general standard, possibly allowing unexpected stress of the battery).

- From the point of view of the product: large changes in the product designs between the different products manufacturers makes impossible to test all aspects of a product safety in a single standard. In addition, some products are designed to pass a standard: this may hinder some unexpected behavior.

Finally, the additional risk is about the inappropriate usage of a standard, which may give the battery user the feeling of purchasing a safe product, although the real safety risks have not been validated in practice. This risk can be covered with a preliminary hazard analysis, which will provide a more specific analysis of the real environment (see Figure 9 in § 5.1.).

5.3. Safety management tools

In practice, no "single device" is capable of fulfilling all the functions for the battery protection. The safety management is obtained with a combination of

- Technology and materials choices to optimize the performance versus reactivity of materials.
- Cell and battery design to optimize the robustness and resistance to environment stress.
- System design, fit and integration in the application.
- Quality product and process control to guarantee the manufacturing steps quality.

As a result, the global safety of a battery requires a much larger approach than the simple selection of materials showing some lower degree of reactivity. Indeed, fire incidents have already occurred with lithium-ion batteries using less reactive electrode materials such as Manganese Dioxide or Iron Phosphate cathode.

In Figure 10, we provide the description of some of the types of protections which are applied to Lithium-ion batteries. These protection systems can be applied at different levels.

Level	**Prevention** (prevent the event)	**Mitigation** (minimize the event)	**Protection** (reduce consequences)
Cell	**Root causes**	X	X
Module/Battery	X	X	X
Application	X		X

FIGURE 10. List of protection measures adopted at various levels.

Depending on their size and application, lithium-ion batteries will use several of the following safety protection devices.

They are categorized in three main types.

CELL HARDWARE

- Cell-Level : Chemical Design Features (electrodes and separator materials)
- Case and Vent Design
- Current interrupt device

SYSTEM HARDWARE

- Electronics Hardware
  - Over-Voltage protection
  - Over-Temperature
  - Cell balancing circuitry
- Electrical Hardware
  - Fusing for over-current
  - Contactors
- Mechanical Hardware at module and systems level
  - Optimum thermal management (heat and fire)
  - Structural protection
  - Gas containment or evacuation systems

SYSTEM SOFTWARE

- Measurement of battery system characteristics
  - Cell/Pack voltage
  - Temperature
  - Current
  - Device feedback
  - Sensor validity
- Default or failure detection and appropriate control actions
  - Battery status and safety control software

Because they are sensitive to overcharge and deep discharge, all Lithium-ion batteries are protected against short-circuiting and have a voltage and current control. These protections are integrated to one or several printed circuit board (PCB) embarked within the battery.

As mentioned earlier, controlling and managing the temperature of the cells and the battery is one of the most important protection measure to be adopted.

In addition, particularly for large batteries, the Battery Management System (BMS) integrates in the software the control of key operational parameters during usage, including state of charge (SoC), current, voltage and the battery's internal and ambient temperatures.

The redundancy of the control functions enhances the reliability of the global system. BMS technologies are constantly being developed to store comprehensive information about the battery use (battery information and traceability) and to regulate even more effectively. Current BMS have a communication system (such as a bus-can) to exchange information with the operating system. The global management of the battery can then be coordinated with the user need, including power and energy availability, or cooling systems control.

The mechanical design of the Lithium-ion cells is proven to be resistant to shocks and vibrations and they can be used safely in a large range of temperatures (typically between -20°C and +60°C). Their mechanical protection is largely ensured by the casing(s) of modules and/or of the battery..

The mechanical and electrical design of the battery depends for a large part on the applications constraints. According the usage specification, the battery is designed to be protected efficiently from usual environmental stress (e.g. external impacts, thermal shocks, etc…) while providing the best service. In addition, the adapted mitigation and protection of the potential hazards are incorporated in the mechanical design (vents, thermal protections against fire propagation, gas treatments, etc…). FIGURE 11 illustrates protections used in a laptop battery.

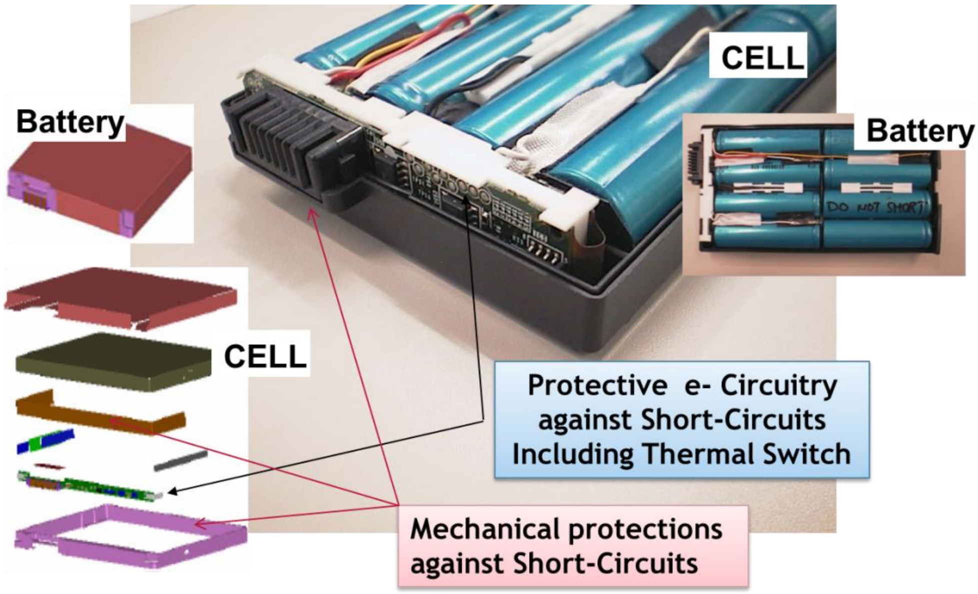

FIGURE 11. Illustrations of system of protection against short circuits used in a Laptop battery pack.

For the protection of the battery, organizational and environmental standards are applied by battery manufacturers ensuring that their manufacturing process is uniform and predictable, without anomalies that could cause safety problems later in the lifecycle. The protection against poor design or manufacturing defaults is generally controlled through the Quality Management systems (QMS). QMS applies directly to the design and manufacturing process, and allow companies to warranty its safety and effectiveness during the production of a battery.
The UN Model Regulation for the Transport of Dangerous Goods specifies that Lithium-ion batteries can only be offered for transport when 'the manufacturer operates under a Quality Management Program'. In practice, this means that all major Lithium-ion battery manufacturers have to follow a QMS that encompasses both external standards and internal company requirements.

There are several important quality standards that a QMS should comply with:

- ISO 9001- A general set of international standards for the processes that create and control the product quality. The manufacturer must test whether the product meet design requirements, regulatory requirements as well as user needs.

- ISO 14001- The core international standard for designing and implementing an effective environmental management system. Helps companies to assess, manage and continuously improve their environmental performance.

- EMAS - A voluntary environmental management system overseen by the European Commission, with stricter requirements than ISO 14001 in several key environmental protection parameters.

6. Conclusion

Safety management is a fundamental measure for all Lithium-ion energy storage systems.

Lithium-ion safety is ensured by a combination of prevention, mitigation and protection systems:

- An application hazard analysis is necessary to adapt the design of the system for each specific application
- Protections are required at all levels: cell, module and battery. Lithium-ion batteries are equipped with electronic protections, mechanical design and electric design incorporating the necessary redundancies in the risk control chain to ensure the reliability of the safety functions

All Lithium-ion batteries are equipped with individual electronic protections to avoid electrical misuse (minimum and maximum voltage protection, current protection, etc…). Their mechanical design makes them resistant to shocks and vibrations and they can be used safely in a large range of temperature (typically between -20°C and +60°C). In order to guarantee the reliability of these protections, the necessary redundancies are introduced in the hazard control chain.

Global systems safety can only be ensured at system and application level. Large battery systems communicate with their operating system in order to coordinate the safety control with the user need, including power and energy availability, or cooling systems control.

In addition, the battery and systems are designed to mitigate the consequences of potential hazards, in order to face the situation of default or abusive usage. The design integrates for example specific vents to safely manage the fume exhausts, and large systems have thermal protections sized to limit the fire propagation.

The global approach to hazard management has made the Lithium-ion battery one of the safest energy storage systems. Billions of electrical and electronic equipments powered by these batteries are used worldwide on a daily basis confirming that the safety of Lithium-ion batteries is well managed.

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