

ENERGY MANAGEMENT FOR MAGNETO-ELECTROCHEMICAL SYSTEM

Field of the Invention

The present invention relates to energy management for a magneto-electrochemical system and particularly, although not exclusively, to a magneto-electrochemical sub-system coupled to a thermal management sub-system and/or magnetically/electrically coupled to an electric motor.

Background

Conventional electrochemical systems including customised or commercially available electrochemical cells and/or batteries can be upgraded to magneto-electrochemical systems through the application of magnetic fields. The magnetic fields can aid the transport of charged ions (e.g., Li⁺ ions) within the electrochemical system, thereby reducing resistances and improving the system's overall performance.

However, electrochemical cells and batteries are sensitive to local heat transport and temperature changes which can create challenges to their integration into wider magneto-electrochemical systems. Moreover, in many implementations, excess electrical, magnetic, and thermal energy from auxiliary sources in the system cannot be utilised effectively. Thus, avoiding thermal, electrical and/or magnetic energy waste is another challenge associated with the integration of electrochemical systems and magneto-electrochemical systems.

The present invention has been devised in light of the above considerations.

Summary of the Invention

In a first aspect, there is provided a system comprising:

a magneto-electrochemical sub-system comprising one or more magnetic field sources, the/each magnetic field source being configured to generate a respective magnetic field through one or more electrochemical cells; and

a thermal management sub-system for performing thermal management on the magneto-electrochemical sub-system, the thermal management sub-system comprising a thermal fluid in thermal communication with the one or more magnetic field sources and/or with the one or more electrochemical cells during use.

By thermally coupling a magneto-electrochemical sub-system to a thermal management sub-system in this way, it can be ensured that the one or more electrochemical cells' performance is enhanced under magneto-electrochemistry conditions while simultaneously satisfying the cells' thermal management requirements to achieve effective operation of the magneto-electrochemical sub-system.

In some examples, the magneto-electrochemical sub-system may comprise the one or more electrochemical cells.

5 In some examples, the one or more electrochemical cells may be enclosed within a first containment structure and the first containment structure may contain the thermal fluid. The first containment structure may comprise one or more sidewalls defining a cell-receiving space for enclosing the one or more electrochemical cells. The first containment structure may partially or fully enclose the one or more electrochemical cells.

10 In some examples, the thermal fluid may be in direct contact with the one or more cells. For example, the thermal fluid may be also contained within the cell-receiving space of the first containment structure. The one or more electrochemical cells may be at least partially, e.g. fully, submersed within the thermal fluid. Alternatively, the thermal fluid may be enclosed within the one or more sidewalls of the first containment structure such that the first containment structure provides a jacket surrounding the cell-receiving space
15 and thus the one or more electrochemical cells.

In some examples, at least one of the one or more magnetic field sources may be contained within the first containment structure. That is, the thermal fluid can mediate exchange of thermal energy between the one or more electrochemical cells and the one or more magnetic field source, e.g. so as to heat the
20 one or more electrochemical cells using heat produced by the one or more magnetic field sources during operation. By providing the one or more electrochemical cells and the at least one magnetic field source in the same containment structure, thermal management of the magneto-electrochemical sub-system can be achieved in a resource- and cost-effective manner. Additionally, or alternatively, at least one of the one or more magnetic field sources may be contained within a second containment structure. The first
25 containment structure may be fluidly and/or thermally isolated from the second containment structure. When the one or more electrochemical cells are provided in the first containment structure separate from the one or more magnetic field sources in the second containment structure, the thermal requirements of the first and second containment structures (and their respective contents) can be managed independently, thereby improving a controllability of the thermal requirements of the overall system. The
30 second containment structure may also comprise thermal fluid. The thermal fluid in the second containment structure may be the same as or different to the thermal fluid in the first containment structure. The second containment structure may comprise one or more sidewalls defining a space for enclosing the at least one magnetic field source. The at least one magnetic field source may be at least partially, e.g. fully, submersed within the thermal fluid contained within the second containment structure.
35 Alternatively, the thermal fluid may be enclosed within the one or more sidewalls of the second containment structure such that the second containment structure provides a jacket surrounding the at least one magnetic field source.

In some examples, the thermal management sub-system may comprise a heat exchanger in thermal
40 communication with (i.e. thermally coupled to) the thermal fluid. The heat exchanger may be a heat sink. For example, this can allow for excess heat to be transferred from the thermal fluid to the heat exchanger, e.g. so as to prevent the one or more electrochemical cells and/or the one or more magnetic field sources

from overheating. Each of the first and second containment structures may be connected to a shared heat exchanger, e.g. a shared heat sink. Alternatively, the heat exchanger may be a first heat exchanger and the thermal management sub-system may further comprise a second heat exchanger such that each of the first and the second containment structure is connected to a respective different one of the first and second heat exchangers. The second heat exchanger may be a heat sink.

In some examples, the thermal management sub-system may be configured to direct the thermal fluid around a heat generating component (acting as a thermal heat supply) and subsequently towards the one or more electrochemical cells. That is, the thermal management sub-system may be configured to perform active thermal management. The thermal management sub-system may comprise one or more pumps configured to pump the thermal fluid from around the heat generating component towards the one or more electrochemical cells. Thus, the thermal management sub-system can drive forced heat transfer between the heat generating component, the thermal fluid and the one or more electrochemical cells. Directing heat-carrying thermal fluid from the heat generating component to the one or more electrochemical cells can help pre-heat the one or more electrochemical cells to a suitable operational temperature and/or maintain the temperature of the one or more electrochemical cells at or above the suitable operational temperature during use.

In some examples, the system may be integrable on board of an electric vehicle comprising an electric motor, and the heat generating component may be the electric motor. Additionally, or alternatively, the heat generating component may be the/each magnetic field source. In examples where the magneto-electrochemical system comprises one or more magnetic field guides as discussed in more detail below, the heat generating component may be the magnetic field guides. That is, thermal fluid may be pumped around any one or any combination of the electric motor and/or the one or more magnetic field sources and/or the one or more magnetic field guides, each of which can generate heat in use to act as a heat generating component.

In some examples, the magnetic field produced by the/each magnetic field source may permeate the thermal fluid. The application of a magnetic field through the thermal fluid can create an advantageous stirring effect in the thermal fluid, thereby enhancing heat transfer. The stirring effect may be enhanced through the addition of magnetically susceptible additives to the thermal fluid and/or by configuring the/each magnetic field source to produce a changing magnetic field through the thermal fluid, as discussed in more detail below.

In some examples, the thermal fluid may be a liquid. For example, the liquid may be any one or any combination of dielectric fluids such as water, water-glycol, ethylene glycol, fluorinated ethers, and/or inhibitors.

In some examples, the thermal fluid (e.g. liquid) may comprise magnetically susceptible additives agitable by the magnetic field produced by the one or more magnetic field sources. Conveniently, agitating the magnetically susceptible additives within the thermal fluid can further promote the stirring effect in the thermal fluid thereby improving heat transfer. The magnetically susceptible additives may

comprise magnetically susceptible particles and/or filings and/or shavings. The magnetically susceptible particles/filings/shavings may be ferromagnetic (e.g. iron-comprising) particles and/or filings and/or shavings. The magnetic field produced by the/each magnetic field source may be a changing magnetic field, as discussed in more detail below. The changing magnetic field can be configured so as to
5 simultaneously enhance the performance (e.g. ion transport and/or capacity) of the/each electrochemical cell by subjecting the/each electrochemical cell to magneto-electrochemical conditions and to promote a stirring effect in the thermal fluid. For example, the changing magnetic field may be configured to be a rotating magnetic field to create a rotational stirring effect.

10 Instead of a liquid, the thermal fluid may be a gas. For example, the gas may be any one or any combination of air and/or an inert gas such as nitrogen. When the thermal fluid is gas, the thermal management sub-system may comprise one or more fans configured to direct the thermal fluid from the heat generating component towards the one or more electrochemical cells. For example, the one or more fans may be mounted on or located in the vicinity of the heat generating component. The one or more
15 fans may be mounted on the one or more magnetic field sources when the heat generating component is the one or more magnetic field sources. The one or more fans can enhance convective heat transfer between the heat generating component and the one or more electrochemical cells.

The one or more electrochemical cells may be in thermal communication with the one or more magnetic field sources. The one or more electrochemical cells may be in thermal communication with the one or more magnetic field sources via electric circuitry, as discussed in more detail below in relation to the second aspect.

The thermal management sub-system may comprise a controller for controlling the magnetic field and/or an amount of heat generated by the/each magnetic field source. Conveniently, the controller can
25 simultaneously control the thermal management of the system as well as its magneto-electrochemical performance according to the system's requirements. The controller may be configured in one or more of the ways described with reference to the second aspect below.

30 In a second aspect, there is provided a system comprising:
a magneto-electrochemical sub-system comprising one or more magnetic field sources, the/each magnetic field source being configured to generate a respective magnetic field through one or more electrochemical cells, wherein in use the one or more magnetic field sources are in thermal communication with the one or more electrochemical cells; and
35 a thermal management sub-system for performing thermal management on the magneto-electrochemical sub-system, the thermal management sub-system comprising a controller for controlling the magnetic field and a resulting amount of heat generated by the/each magnetic field source.

At least one of the one or more electrochemical cells may be in direct contact with at least one of the one or more magnetic field sources. Thus, heat transfer between the one or more electrochemical cells and
40 the one or more magnetic field sources may be conductive. Additionally, or alternatively, the one or more electrochemical cells may be arranged in close proximity to at least one of the one or more magnetic field

sources. Thus, heat transfer between the one or more electrochemical cells and the at least one magnetic field source may be radiative and/or convective. The system of the second aspect allows the heat generated by the/each magnetic field source during operation to be harnessed for thermal management of the magneto-electrochemical sub-system (e.g. for pre-heating and/or maintaining a suitable operational temperature of the one or more electrochemical cells during use). Conveniently, the controller can simultaneously control the thermal management of the system as well as its magneto-electrochemical performance according to the system's requirements.

The magneto-electrochemical sub-system may further comprise electric circuitry. The electric circuitry may be electrically connected to the one or more electrochemical cells. The electric circuitry may be for electrically connecting the one or more electrochemical cells to an electric power supply. The electric circuitry may comprise one or more cables. For example, the electric circuitry may comprise one or more positive battery cables for connection to positive terminals of the one or more cells, and the electric circuitry may comprise one or more negative battery cables for connection to negative terminals of the one or more cells.

The one or more electrochemical cells may be in thermal communication with the one or more magnetic field sources via the electric circuitry. In this way, the electric circuitry can facilitate heat transfer between the one or more magnetic field sources and the one or more electrochemical cells, thereby acting as a heat exchanger

In some examples, the electric circuitry may be at least partially interposed between the one or more electrochemical cells and the one or more magnetic field sources. In some examples, at least a part of the electric circuitry may be passed through and/or around the one or more magnetic field sources. In this way, the one or more magnetic field sources can transfer heat to the electric circuitry, which in turn can transfer heat to the one or more electrochemical cells

In some examples, at least a part of the electric circuitry may be arranged in a plane. The plane may be parallel to a plane in which the magnetic field sources are arranged. The electric circuitry may be arranged so as to be adjacent to a side of the magnetic field source(s) which is proximal or distal the one or more electrochemical cells.

The electric circuitry may be at least partially arranged in a serpentine or a zig-zag shape. The serpentine or zig-zag shape may include a plurality of bends, connected by a plurality of substantially straight segments. In some examples, the magnetic field sources may be arranged in an array or a grid. The electric circuitry may be arranged in a serpentine or zig-zag configuration around the magnetic field sources. By arranging the electric circuitry in a serpentine or a zig-zag manner relative to the magnetic field sources, the amount (length) of electric circuitry which is in thermal communication with the magnetic field sources can be increased, thereby improving heat exchange between the circuitry and the magnetic field sources.

In some examples, the/each magnetic field source may be an electromagnet. The/each electromagnet may comprise a core. In some examples, at least a part of the electric circuitry (e.g. at least a part of the positive and/or negative battery cables) may be threaded through one or more of the cores of the one or more electromagnets.

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All of the arrangements of the electric circuitry relative to the magnetic field source(s) and the electrochemical cell(s) described above could be combined with one another, except where such a combination is clearly impermissible or expressly avoided.

- 10 When the/each magnetic field source is an electromagnet, the controller may be configured to control a type (e.g. direct current (DC)/alternating current (AC)) and/or a frequency and/or a magnitude and/or a polarity (direction) of an electric current supplied to the/each electromagnet. The controller may be configured to control the frequency of the electric current supplied to the/each electromagnet such that the frequency is at least 0.001Hz, or at least 0.01Hz, or at least 0.1Hz, or at least 1Hz, or at least 10Hz,
- 15 or at least 100Hz, or at least 1,000Hz, or at least 5,000Hz, or at least 7,500 Hz. The controller may be configured to control the frequency of the electric current supplied to the/each electromagnet such that the frequency is 10,000Hz or less, or 7,500Hz or less, or 5,000 Hz or less, or 1,000Hz or less, or 100Hz or less, or 10Hz or less, or 1Hz or less.
- 20 In some examples, the controller may be configured to cause a mixture of DC and AC to be supplied to the/each electromagnet. The controller may be configured to cause DC (and/or a high frequency AC) to be supplied to the/each electromagnet e.g. to perform pre-heating (such as inductive pre-heating) of the magneto-electrochemical sub-system. The controller may be configured to subsequently cause an AC to be supplied to the/each electromagnet to control the/each generated magnetic field. In some examples,
- 25 the controller may be configured to cause a mixture of different alternating currents (e.g. alternating currents having different frequencies) to be supplied to the/each electromagnet. For example, a variable high frequency AC may be supplied for temperature control. The variable high frequency AC may be overlaid or pulsed with a lower frequency AC for magnetic control. In some examples, the controller may be configured to cause a DC to be supplied to the/each electromagnet, e.g. to perform pre-heating of the magneto-electrochemical sub-system, the DC may be overlaid or pulsed with a low-frequency AC for magnetic control. Additionally, or alternatively, the controller may be configured to cause arbitrary
- 30 waveform currents to be supplied to the/each electromagnet.

- In some examples, the system of the first or second aspect may further comprise an electric motor,
- 35 wherein the electric motor may be electrically and/or magnetically coupled to the magneto-electrochemical sub-system. The electric motor may be the electric motor of an electric vehicle and the system may be integrated on board of the electric vehicle. The magneto-electrochemical sub-system may be magnetically and/or electrically coupled to the electric motor in any of the ways discussed with reference to the third and fourth aspects below.

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The system of the second aspect may have any combination of features discussed with reference to the system of the first aspect. For example, the magneto-electrochemical sub-system may be thermally

managed both by controlling the magnetic field and the resulting amount of heat generated by the/each magnetic field source as discussed with reference to the second aspect, and by using a thermal fluid as discussed with reference to the first aspect.

- 5 In some examples there may be provided a method which may implement any one or more features disclosed herein. The method may comprise providing the system of the second aspect (or the system of the first aspect when comprising a controller for controlling the magnetic field and/or a resulting amount of heat generated by the/each magnetic field source) and controlling the magnetic field and the resulting amount of heat generated by the/each magnetic field source. Controlling the magnetic field and the
- 10 amount of generated heat may involve supplying a mixture of DC and AC to the/each electromagnet, e.g. supplying a DC (and/or a high-frequency AC) to the/each electromagnet (e.g. to perform pre-heating of the magneto-electrochemical sub-system) and subsequently supplying AC to the/each electromagnet (e.g. to control the/each generated magnetic field). In some examples, controlling the magnetic field and the amount of generated heat may involve supplying a mixture of different alternating currents (e.g.
- 15 alternating currents having different frequencies) to the/each electromagnet. For example, the method may comprise supplying a variable high frequency AC (e.g. for temperature control) overlaid or pulsed with a lower frequency AC (e.g. for magnetic control). When the method comprises supplying a DC to the/each electromagnet, e.g. to perform pre-heating of the magneto-electrochemical sub-system, the method may further comprise overlaying or pulsing a low-frequency AC with the DC, e.g. for magnetic
- 20 control. Additionally, or alternatively, the method may comprise supplying a arbitrary waveform currents to the/each electromagnet.

In a third aspect, there is provided a system comprising:

- a magneto-electrochemical sub-system comprising one or more magnetic field sources, the/each
- 25 magnetic field source being configured to generate a respective magnetic field through one or more electrochemical cells; and
- an electric motor electrically coupled to the magneto-electrochemical sub-system.

- In this way, excess electric energy produced by the electric motor (e.g. generated from regenerative
- 30 breaking of the electric vehicle) may be supplied to the magneto-electrochemical sub-system, thereby reducing energy waste. For example, the excess electric energy may be supplied to the one or more magnetic field sources so as to drive them (e.g. when the/each magnetic field source is an electromagnet). Additionally, or alternatively, the excess electric energy may be supplied to the one or more electrochemical cells to charge them. The electric motor may be electrically coupled to the
- 35 magneto-electrochemical sub-system via an electrical connection (such as a cable or a wire).

In some examples, the system may further comprise one or more magnetic field guides and the magneto-electrochemical sub-system may be further magnetically coupled to the electric motor via the one or more magnetic field guides.

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In a fourth aspect, there is provided a system comprising:

a magneto-electrochemical sub-system comprising one or more magnetic field sources, the/each magnetic field source being configured to generate a respective magnetic field through one or more electrochemical cells;

one or more magnetic field guides; and

- 5 an electric motor magnetically coupled to the magneto-electrochemical sub-system via the one or more magnetic field guides.

In this way, excess magnetic energy produced by the electric motor may be supplied to the magneto-electrochemical sub-system, thereby reducing energy waste. For example, the one or more magnetic field
10 sources of the magneto-electrochemical sub-system may together act as primary magnetic field generator to provide a primary magnetic field through the/each electrochemical cell and the electric motor may act as a secondary magnetic field generator with the excess magnetic energy being guided to the one or more electrochemical cells as a secondary magnetic field.

- 15 The magneto-electrochemical sub-system discussed with reference to any of the aspects above may have any one or combination of the optional features discussed below.

In some examples, the magneto-electrochemical sub-system may comprise the one or more electrochemical cells. The/each electrochemical cell may be a Li-ion cell or battery, a secondary battery
20 such as positive ion secondary battery, a solid-state cell/battery comprising solid electrolyte, a Na-ion cell or battery, an electrolyser, or a fuel cell.

The magneto-electrochemical sub-system may be electrically connectable to an electric power supply, e.g. to charge the one or more electrochemical cells and/or to power (drive) the one or more magnetic
25 field sources so as to generate the magnetic field(s). The magneto-electrochemical sub-system may be electrically connectable/connected to an electric load e.g. to discharge the electrochemical cells. The electric load may be auxiliary equipment on board of an electric vehicle, or an electric motor such as a driving motor for driving the vehicle. Additionally, or alternatively, the one or more electrochemical cells may be electrically connected to the one or more magnetic field sources (e.g. when the/each magnetic
30 field source is an electromagnet). Thus, any excess electric energy generated by the one or more electrochemical cells resulting from the performance enhancement under magneto-electrochemical conditions can be supplied to the/each magnetic field source. This can make efficient use of electric energy within the magneto-electrochemical sub-system.

- 35 The system may comprise a primary magnetic field generator and a secondary magnetic field generator. The primary magnetic field generator may be provided by at least one of the one or more magnetic field sources. The secondary magnetic field generator may be provided by at least one of the one or more magnetic field sources, different from the primary magnetic field generator. Additionally, or alternatively, when the system comprises the electric motor, the secondary magnetic field generator may be provided
40 by the electric motor. The one or more electrochemical cells may be electrically connected to the primary and/or secondary magnetic field generator so as to supply electric energy thereto.

- In some examples, the/each magnetic field source may be a plurality of electromagnets. The plurality of electromagnets may be arranged in an array and/or a grid and/or a stack. The plurality of electromagnets may be sequentially activated e.g. to produce a desired magnetic field signature. For example, the controller of the system of the first/second aspect may perform sequential control on the plurality of electromagnets to sequentially activate them (i.e. drive them). Sequentially activating the electromagnets may be beneficial for subjecting the one or more electrochemical cells to pre-determined magneto-electrochemical and/or for stirring the thermal fluid as discussed with reference to the first aspect (e.g. when the thermal fluid is a liquid and/or comprises magnetically susceptible additives).
- 10 In some examples, the/each magnetic field may be a changing magnetic field. Conveniently, configuring the/each magnetic field source to produce a changing magnetic field through the/each electrochemical cell can improve ion transport within the/each cell, thereby reducing/homogenising local resistances within the/each cell. This can lead to improvements in charging/discharging speeds and/or in cell capacity.
- 15 In some examples, the/each magnetic field may be a pulsing, and/or an oscillating and/or a rotating magnetic field. The/each changing magnetic field may vary in one and/or two and/or three spatial dimensions. The/each changing magnetic field may vary in magnitude and/or frequency and/or polarity (direction). The/each changing magnetic field may vary in a continuous manner over time, i.e. the/each changing magnetic field may be a continuously varied changing magnetic field. That is, the changing magnetic field amounts to more than simply a periodic reversal in direction, and as such consecutive instantaneous snapshots of the/each continuously varied changing magnetic field will differ from one another at least in magnitude and/or frequency and/or polarity (direction). This is particularly advantageous in view of the fact that ions (such as Li⁺ ions) within an electrochemical cell navigate a tortuous path that meanders across many directions on their way from the cell's cathode to the cell's anode. This is because electrochemical cells, such as Li-ion cells, have complex micro- and nano-structures with electrodes and optionally a separator that each contain tortuosities and obstructions in all spatial directions. Furthermore, crystals within the electrode particles forming the electrodes are not only orientated in many directions, but are also known to change direction during operation, adding further complexity to the ion motion. Thus, configuring the/each magnetic field source to produce a continuously varied changing magnetic field can ensure that ion transport within the/each electrochemical cell is optimally enhanced. Alternatively, the/each changing magnetic field may vary in a periodic, e.g. step-wise, manner.
- 20 25 30 35 40 In some examples, the magneto-electrochemical sub-system may comprise one or more magnetic field guides configured to guide the generated magnetic field by the/each magnetic field source to the/each electrochemical cell, and the/each electrochemical cells may be in thermal communication with the/each field guide. The/each magnetic field guide may be connected to a heat exchanger such as a heat sink.
- When the system comprises one or more magnetic field guides, the/each magnetic field guide may be thermally coupled to (i.e. in thermal communication with) the magneto-electrochemical sub-system. For example, the/each magnetic field guide may be thermally coupled to the one or more electrochemical

cells. In this way, heat generated by the/each magnetic field guide may be used to heat (e.g. pre-heat) the one or more electrochemical cells. The/each magnetic field guide may comprise a plate and/or a rod and/or an electromagnetic coil. For example, the system may comprise a plurality of magnetic field guides at least one of which is a plate (e.g. a metallic plate) and at least one of which is a rod (e.g. metallic rod).

- 5 That is, the system may comprise an assembly of magnetic field guides, which may be of different geometries and/or materials or of the same geometry and/or material. The/each magnetic field guide may be formed of any combination of metal, e.g. ferromagnetic metal, and/or ferrite, and/or metal oxide such as iron oxide. Conveniently, magnetic field guides can be used to selectively direct magnetic field lines of a generated magnetic field in a predetermined manner. For example, an assembly of metallic plates
10 and/or electromagnetic coils and/or metallic rods can affect the distribution of the magnetic field lines through a selected region in space, e.g. so as to focus them at/divert them away from a specific spatial location.

- In some examples, the thermal management sub-system may comprise a controller for controlling the
15 thermal management sub-system and a feedback loop for providing feedback to the controller. The feedback may be feedback from the magneto-electrochemical sub-system and/or from the electric motor electrically and/or magnetically coupled to the magneto-electrochemical sub-system. For example, in the system of the first aspect, the controller may vary a flow rate of the thermal fluid through/around the magneto-electrochemical sub-system according to a state of charge of the/each electrochemical cell. In
20 the system of the second aspect, the controller for controlling the thermal management sub-system may be the same as the controller for controlling the magnetic field and the amount of heat generated by the/each magnetic field source.

- The system of any aspect may be integrable on board of an electric vehicle or a hybrid electric vehicle.
25 The system may be integrable in an energy storage facility, such as stationary home energy storage. The system may be integrable in a manufacturing facility for manufacturing electrochemical cells under magneto-electrochemical conditions using the magneto-electrochemical sub-system.

- In a fifth aspect, there is provided an electric vehicle comprising the system of any one of the first, the
30 second, the third, or the fourth aspect.

The invention includes the combination of the aspects and preferred features described except where such a combination is clearly impermissible or expressly avoided.

Summary of the Figures

- 35 Embodiments and experiments illustrating the principles of the invention will now be discussed with reference to the accompanying figures in which:

Figure 1 schematically shows a system according to an embodiment of the present invention;

Figure 2 schematically shows an example implementation of the system of Figure 1;

Figures 3 and 4 respectively show a perspective and a side view of an alternative example implementation of the system of Figure 1;

Figure 5 schematically shows an alternative implementation of the system of Figure 1;

Figure 6 shows a variant of the implementation of Figure 5;

- 5 **Figure 7** schematically shows a plot of different electric field profiles to be applied to a magnetic field source;

Figure 8 schematically shows a system according to an embodiment of the present invention;

Figures 9 and 10 respectively show a top view and a side view of an example implementation of the system of Figure 8;

- 10 **Figure 11** schematically shows a system according to an embodiment of the present invention;

Figure 12 schematically shows an example implementation of the system of Figure 11;

Figure 13 shows a perspective view of a different example implementation of the system of Figure 11;

Figure 14 schematically shows an electric vehicle comprising any variant of the system of Figures 1-13.

Figure 15 schematically shows a system according to an embodiment of the present invention;

- 15 **Figures 16A and 16B** respectively show an assembled and an exploded view of a system according to an embodiment of the present invention; and

Figures 17A and 17B respectively show an assembled and an exploded view of a system according to an embodiment of the present invention.

20 ***Detailed Description of the Invention***

Aspects and embodiments of the present invention will now be discussed with reference to the accompanying figures. Further aspects and embodiments will be apparent to those skilled in the art.

- 25 With reference to Figure 1, there is provided a system 100 comprising a magneto-electrochemical sub-system 1 and a thermal management sub-system 10. The magneto-electrochemical sub-system 1 comprises one or more magnetic field sources 3, the/each magnetic field source being configured to generate a respective magnetic field through one or more electrochemical cells 2. In this example, the magneto-electrochemical sub-system 1 comprises the one or more electrochemical cells 2 and each electrochemical cell 2 is a Li-ion battery. The magnetic field sources 3 together provide a primary
- 30 magnetic field generator. The magneto-electrochemical sub-system 1 can optionally comprise one or more magnetic field guides 4 configured to guide the generated magnetic field by the/each magnetic field source 3 to the/each electrochemical cell 2. The one or more electrochemical cells 2 are thermally coupled to the one or more magnetic field sources 3 and to the one or more magnetic field guides 4 (as denoted by dashed lines (ii)).

In the present example, the magnetic field produced by the/each magnetic field source 3 is a changing magnetic field such as a pulsing, and/or an oscillating and/or a rotating magnetic field. The/each changing magnetic field may vary in one and/or two and/or three spatial dimensions. The/each changing magnetic field may vary in magnitude and/or frequency and/or polarity (direction). The/each changing magnetic field may vary in a continuous manner, i.e. the/each changing magnetic field may be a continuously varied changing magnetic field. That is, consecutive instantaneous snapshots of the/each changing magnetic field will differ from one another at least in magnitude and/or frequency and/or polarity (direction). Alternatively, the/each changing magnetic field may vary in a periodic, e.g. step-wise manner.

10 The system 100 further comprises a thermal management sub-system 10 for performing thermal management on the magneto-electrochemical sub-system 1. The/each electrochemical cell 2 is thermally coupled to a heat generating component 16 (as demonstrated by dashed line (i)). The heat generating component 10 may form part of the thermal management sub-system 10. The thermal management sub-system 10 comprises a thermal fluid in thermal communication with the one or more magnetic field
15 sources 3 and/or with the one or more electrochemical cells 2 during use. The thermal management sub-system also comprises a heat exchanger 18 which is a heat sink in this example. As shown in Figure 1 (via dashed lines (iii)), each of the one or more electrochemical cells 2, the one or more magnetic field sources 3, and the one or more magnetic field guides 4 is thermally coupled to the heat exchanger 18. This can prevent these components from overheating.

20 Multiple implementations of the system 100 of Figure 1 are possible. A first example implementation is discussed with reference to Figure 2. In this example, the one or more magnetic field sources 3 is two magnetic field sources each of which is an electromagnet. The electromagnet 3 are arranged in a stack. The electrochemical cell 2 is arranged in the vicinity of and in thermal communication with at magnetic
25 field sources 3. Specifically, the electrochemical cell 2 and one of the magnetic field sources 3 are enclosed within a first containment structure 12 (i.e. within a cell-receiving space of the first containment structure defined by its sidewalls). The other of the magnetic field sources 3 is enclosed within a second containment structure 13. Each of the first 12 and the second containment structure 13 contains thermal fluid 11. The thermal fluid in this example is liquid. The electrochemical cell 2 as well as the magnetic field
30 sources 3 are each fully submersed within the thermal fluid 11.

The magnetic fields produced by both magnetic field sources 3 permeate both the electrochemical cell 2 and the thermal fluid 11. The magnetic fields create a stirring effect in the thermal fluid to enhance heat transfer. The thermal fluid contains magnetically susceptible additives, such as iron particles and/or filings
35 and/or shavings. The magnetically susceptible additives are agitable by the magnetic fields generated by the magnetic field sources 3, thereby enhancing the stirring effect in the thermal fluid. Both the first containment structure 12 and the second containment structure 13 are connected to the same heat exchanger 18 which is a heat sink. In this way, excess heat can be transferred from the thermal fluid to the heat sink so as to prevent the one or more electrochemical cells 2 and the one or more magnetic field
40 sources 3 from overheating, thereby actively cooling the magneto-electrochemical sub-system. The

magnetic field lines 6 signify the direct of the produced magnetic field through the thermal fluid 11 and the electrochemical cell 2. Lines 6' signify a direction of heat transfer between the first containment structure 12 and the second containment structure 13.

- 5 The thermal management sub-system 10 is configured to direct the thermal fluid around the heat generating component 16 (acting as a thermal heat supply) and subsequently towards the electrochemical cell. To this end, the thermal management sub-system 10 comprises pumps 14. In this example, the thermal management sub-system 10 comprises a pump 14 fluidly connected to the first containment structure 12 and a further pump 14 fluidly connected to the second containment structure 13.
- 10 Both magnetic field sources 3 can act as a heat generating component 16. Thus, the thermal management sub-system can 10 drive forced heat transfer between the magnetic field sources 2, the thermal fluid 11 and the electrochemical cell 2.

- The thermal management sub-system 10 comprises a controller 5 for controlling the magnetic field and the resulting amount of heat generated by each of the two magnetic field source 3 or just the magnetic field source 3 enclosed within the first containment structure 12. The controller can control the magnetic field and the resulting amount of heat generated by controlling a type (e.g. direct current (DC)/alternating current (AC)) and/or a frequency and/or a magnitude and/or a polarity (direction) of an electric current supplied to the/each electromagnet 3 e.g. via an electrical supply 7. This is described in more details with reference to Figure 7. The controller can also vary a flow rate of the thermal fluid through/around the cell 2 and the magnetic field sources 3 according to a state of charge of the/each electrochemical cell 2 based on feedback from a feedback loop.
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- A variant of the example implementation of Figure 2 is discussed with reference to Figures 3 and 4. This implementation differs in that there is a plurality of electrochemical cells 2 and the first containment structure 12 only contains the electrochemical cells 2 but not the magnetic field source(s) 3. Instead, the magneto-electrochemical sub-system 1 comprises a plurality of magnetic field sources 3, each of which is an electromagnet, and the plurality of magnetic field sources 3 together provide a primary magnetic field generator upon which the first containment structure rests such that the first containment structure is in direct contact with the magnetic field sources 3. This promotes conductive heat transfer between the magnetic field sources 3 (acting as a heat generating component 16) and the electrochemical cells 2 via the walls of the first containment structure 12 and the thermal fluid 11. Furthermore, in this example, the electrochemical cells are only partially submersed within the thermal fluid 11. The thermal management sub-system comprises fans 15 configured to direct air from the magnetic field sources 3 to the first containment structure 12 comprising the electrochemical cells 2 to enhance heat transfer therebetween.
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- A yet further example implementation 100b of the system 100 of Figure 1 is discussed with reference to Figures 5, 6 15, 16, and 17. This implementation differs from the implementations discussed above as the thermal fluid is gas such as air, instead of a liquid. The thermal management sub-system 15 comprises fans 15 to direct air from the magnetic field source(s) 3 to the electrochemical cell(s) 2. The electrochemical cell(s) can either be in direct contact with the magnetic field source(s) 3 as shown in Figure 5 to promote conductive heat transfer in addition to convective heat transfer realised by the fan(s)
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15, or the electrochemical cell(s) 2 can be spaced from the magnetic field source(s) 3 via magnetic field guides 4 as shown in Figure 6. More specifically, the example system 100b comprises an assembly of magnetic field guides 4 comprising a metallic plate magnetic field guide 4a and metallic rod magnetic field guides 4b. The metallic rods are interposed between the magnetic field sources 3 (provided as a primary magnetic field generator as in Figures 3 and 4) and the metallic plate 4a. The metallic plate supports the electrochemical cells 2 such that it is in direct contact with and thus in thermal communication with the electrochemical cells 2. Each magnetic field guide 4a, 4b is of metal, e.g. ferromagnetic metal. The assembly of magnetic field guides 4 guides the magnetic field generated by the magnetic field sources 3 to the electrochemical cells 2 as shown by the magnetic field line 6. Heat from the magnetic field sources 3 is also transferred from the magnetic field sources 3 to the electrochemical cells via the metallic rods 4a and the metallic plate 4a through conductive heat transfer.

Figures 15-17 show a further example implementation of the system. In this implementation, the magneto-electrochemical sub-system comprises electric circuitry 22 which is electrically connected to the one or more electrochemical cells 2 and electrically connectable to an electric power supply. The electric circuitry 22 comprises a positive battery cable for connection to a positive terminal 21 of the shown electrochemical cell, and a negative battery cable for connection to a negative terminal 21 of cell. The electrochemical cell 2 is in thermal communication with the magnetic field sources 3 via the electric circuitry 22. In this way, the electric circuitry 22 can facilitate heat transfer from the magnetic field source 3 to the electrochemical cell 2.

In the examples of Figures 16 and 17, the magneto-electrochemical sub-system comprises a plurality of magnetic field sources 3, which are arranged in an array (see Figs 16A-16B) or in a grid (see Figs 17A-17B) on a planar support 23. The magnetic field sources 3 are electromagnets. In the example of Figures 16A and 16B, a part of the electric circuitry 22 is arranged in a zig-zag shape and interposed between the planar support 23 and the magnetic field sources 3. In the example of Figures 17A and 17B, a part of the electric circuitry 22 is arranged in a serpentine shape and interposed between the planar support 23 and the magnetic field sources 3. The electric circuitry 22 thus comprises a plurality of bends connected by a plurality of straight segments, such that it passes around the magnetic field sources 3. In this way, the amount (length) of electric circuitry which is in thermal communication with the magnetic field sources 3 can be increased to promote heat exchange therebetween.

The electric circuitry 22 can be arranged so as to be adjacent to a side of the magnetic field sources 3 which is distal the electrochemical cell 2 (as shown in Figure 15), or alternatively, proximal the electrochemical cell 2.

Other implementations are also possible. For example, at least a part of the electric circuitry 22 may be passed through the one or more magnetic field sources 3. For example, at least a part of the electric circuitry 22 (e.g. at least a part of the positive and/or negative battery cables) may be threaded through one or more of the cores of the electromagnets 3.

As discussed above, different implementations of the system 1 comprise a controller 5 for controlling the magnetic field and the resulting amount of heat generated by the magnetic field sources 3. As already mentioned, the controller 5 may be configured to control a type (e.g. direct current (DC)/alternating current (AC)) and/or a frequency and/or a magnitude and/or a polarity (direction) of an electric current supplied to the/each magnetic field source 3, when the/each magnetic field source is an electromagnet. Examples of different currents that can be supplied to the magnetic field sources 3 are shown in Figure 7. These include a low/high DC pulse, AC on high/low DC baseline, high/low frequency AC, and multi-frequency AC. For example, the controller 5 may be configured to cause a mixture of DC and AC to be supplied to the/each electromagnet 3. The controller may be configured to cause DC to be supplied to the/each electromagnet 3 e.g. to perform pre-heating of the magneto-electrochemical sub-system 1. The controller 3 may be configured to subsequently cause an AC to be supplied to the/each electromagnet 3 to control the/each generated magnetic field. In some examples, the controller may be configured to cause a mixture of different alternating currents (e.g. alternating currents having different frequencies) to be supplied to the/each electromagnet 3 (as seen in the far right of Figure 7). For example, a variable high frequency AC may be supplied for temperature control overlaid or pulsed with a lower frequency AC for magnetic control. Different waveforms to those shown in Figure 7 are also possible. For example, arbitrary waveform currents can be supplied to the magnetic field sources 3.

Next, a different system 200 is discussed with reference to Figures 8-10. The system 200 of this example comprises an electric power supply 7 connected to the magneto-electrochemical sub-system 1 and more specifically to each of the electrochemical cells 2 and the magnetic field sources 3 (as denoted by dashed lines (i)). The electric power supply 7 can thus charge the one or more electrochemical cells and/or power (drive) the one or more magnetic field sources so as to generate the magnetic field(s). The magneto-electrochemical sub-system 1 is further electrically connected to an electric load 8 e.g. to discharge the electrochemical cells (see dashed line (iia)). The electric load may be auxiliary equipment on board of an electric vehicle. Furthermore, the one or more electrochemical cells 2 are electrically connected to the one or more magnetic field sources 3 (e.g. when the/each magnetic field source 3 is an electromagnet). This is denoted by dashed line (iib) in Figure 8. The one or more electrochemical cells 2 are also electrically connected to an electric motor 17 (dashed line (iic)). In this way, electric energy generated by the electrochemical cells 2 can not only be supplied to the load 8 but also to the magnetic field sources 3 and to the electric motor so as to drive them. Specifically, any excess electric energy generated by the one or more electrochemical cells 2 resulting from the performance enhancement under magneto-electrochemical conditions can be supplied to magnetic field source(s) 3 and to the electric motor 17 to reduce waste of electric energy within the system 200.

Additionally, the electric motor 17 is electrically connected to the magnetic field source(s) 3 (dashed line (iv)). This allows electric energy to be supplied from the electric motor 17 to the magnetic field source(s) 3 so as to drive them. For example, excess electric energy generated by the electric motor 17 e.g. via regenerative braking of a vehicle, can be supplied to the magnetic field sources 3.

This system 200 allows exchange of electric energy between the magneto-electrochemical sub-system and the electric motor 17 so as to make an efficient use of electrical energy within the wider system, re-directing excess energy as required instead of wasting it.

5 An example implementation of the system 200 is discussed with reference to Figures 9 and 10. In this implementation, the electrochemical cells 2 are supported by the magnetic field sources 3 which are each an electromagnet and together provide a primary magnetic field generator. The magnetic field sources 3 are electrically connected to the electric motor 17 such that excess energy from the electric motor 17 can be supplied to the magnetic field sources 3 so as to drive them. Thermal management of the magneto-
10 electrochemical sub-system 1 is enabled by conductive heat transfer via the direct contact between the electrochemical cells 2 and the magnetic field sources 3, and via convective heat transfer enabled by the fans 15 mounted to the primary magnetic field generator.

A final system 300 is discussed with reference to Figures 11-13. In addition to the magneto-
15 electrochemical sub-system 1, the system 300 comprises an electric motor 17 magnetic coupled to the magneto-electrochemical sub-system 1 via one or more magnetic field guides 4 (dashed line (iia)). The magnetic field guides are magnetically coupled to the magnetic field source(s) 3 (dashed line (ii)) as well as to the electrochemical cell(s) 2 (dashed line (iib)). The magnetic field source(s) 3 are magnetically coupled to the electrochemical cell(s) 2 (dashed line (i)). In this way, excess magnetic energy produced
20 by the electric motor 17 can be supplied to the magneto-electrochemical sub-system 1, thereby reducing energy waste. That is, the one or more magnetic field sources 3 of the magneto-electrochemical sub-system 1 together act as primary magnetic field generator and the electric motor 17 acts as a secondary magnetic field generator with the excess magnetic energy being guided to the one or more electrochemical cells 2 as a secondary magnetic field.

25 An example implementation of this system 300 is discussed with reference to Figure 12. In this example, the magnetic field 6 produced by the electric motor 17 (which may be the electric motor of a vehicle), is picked up and guided by magnetic field guides 4 to both the magnetic field source(s) 3 and to the electrochemical cell(s) 2. With specific reference to Figure 13, the magnetic field guides 4 can be
30 provided by an assembly of metallic rods 4b and a metallic plate 4a. The assembly can help guide the magnetic field generated by the electric motor 17 to the magnetic field sources 3 (some provided in the vicinity of the electrochemical cells 2 and others in direct contact with the cells 2) and to the electrochemical cells 2 themselves.

35 Finally, a vehicle comprising the system 100 of Figure 1 (according to any one of its implementations) is shown in Figure 14. The vehicle 20 may instead comprise the system 200 of Figure 8 according to any one of its implementations, or the system 300 of Figure 11, according to any one of its implementations.

The features disclosed in the foregoing description, or in the following claims, or in the accompanying
40 drawings, expressed in their specific forms or in terms of a means for performing the disclosed function,

or a method or process for obtaining the disclosed results, as appropriate, may, separately, or in any combination of such features, be utilised for realising the invention in diverse forms thereof.

While the invention has been described in conjunction with the exemplary embodiments described above,
5 many equivalent modifications and variations will be apparent to those skilled in the art when given this disclosure. Accordingly, the exemplary embodiments of the invention set forth above are considered to be illustrative and not limiting. Various changes to the described embodiments may be made without departing from the spirit and scope of the invention.

10 For the avoidance of any doubt, any theoretical explanations provided herein are provided for the purposes of improving the understanding of a reader. The inventors do not wish to be bound by any of these theoretical explanations.

Any section headings used herein are for organizational purposes only and are not to be construed as
15 limiting the subject matter described.

Throughout this specification, including the claims which follow, unless the context requires otherwise, the word "comprise" and "include", and variations such as "comprises", "comprising", and "including" will be understood to imply the inclusion of a stated integer or step or group of integers or steps but not the
20 exclusion of any other integer or step or group of integers or steps.

It must be noted that, as used in the specification and the appended claims, the singular forms "a," "an," and "the" include plural referents unless the context clearly dictates otherwise. Ranges may be expressed herein as from "about" one particular value, and/or to "about" another particular value. When such a range
25 is expressed, another embodiment includes from the one particular value and/or to the other particular value. Similarly, when values are expressed as approximations, by the use of the antecedent "about," it will be understood that the particular value forms another embodiment. The term "about" in relation to a numerical value is optional and means for example +/- 10%.

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Claims:

1. A system comprising:
a magneto-electrochemical sub-system comprising one or more magnetic field sources, the/each
5 magnetic field source being configured to generate a respective magnetic field through one or more
electrochemical cells, wherein in use the one or more magnetic field sources are in thermal
communication with the/the one or more electrochemical cells; and
a thermal management sub-system for performing thermal management on the magneto-
electrochemical sub-system, the thermal management sub-system comprising a controller for controlling
10 the magnetic field and a resulting amount of heat generated by the/each magnetic field source.
2. The system of claim 1 wherein the/each magnetic field source is an electromagnet, and the
controller is configured to control a type and/or a frequency and/or a magnitude and/or polarity of an
electric current supplied to the/each electromagnet.
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3. The system of claim 1 or 2 wherein the magneto-electrochemical sub-system comprises one or
more magnetic field guides configured to guide the generated magnetic field by the/each magnetic field
source to the/each electrochemical cell, and the/each electrochemical cells is in thermal communication
with the/each field guide.
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4. The system of any preceding claim wherein the system further comprises an electric motor,
wherein the electric motor is electrically and/or magnetically coupled to the magneto-electrochemical sub-
system.
- 25 5. The system of any preceding claim wherein:
the magneto-electrochemical sub-system further comprises electric circuitry for electrically
connecting the one or more electrochemical cells to an electric power supply; and
in use, the one or more magnetic field sources are in thermal communication with the one or
more electrochemical cells via the electric circuitry.
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6. The system of claim 5 wherein at least a part of the electric circuitry is passed through and/or
around the one or more magnetic field sources.
7. The system of claim 5 or 6 wherein the electric circuitry is at least partially interposed between
35 the one or more electrochemical cells and the one or more magnetic field sources.
8. A system comprising:
a magneto-electrochemical sub-system comprising one or more magnetic field sources, the/each
magnetic field source being configured to generate a respective magnetic field through one or more
40 electrochemical cells; and
a thermal management sub-system for performing thermal management on the magneto-

electrochemical sub-system, the thermal management sub-system comprising a thermal fluid in thermal communication with the one or more magnetic field sources and/or with the one or more electrochemical cells during use.

5 9. The system of claim 8 wherein the one or more electrochemical cells are enclosed within a first containment structure and the first containment structure contains the thermal fluid.

10. The system of claim 9 wherein the thermal fluid is in direct contact with the one or more cells.

10 11. The system of claim 9 or 10 wherein at least one of the one or more magnetic field sources is contained within the first containment structure.

12. The system of any one of claims 9-11 wherein at least one of the one or more magnetic field sources is contained within a second containment structure fluidly isolated from the first containment
15 structure.

13. The system of any one of claims 8 to 12 wherein the thermal management sub-system is configured to direct the thermal fluid around a heat generating component and subsequently towards the one or more electrochemical cells.

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14. The system of claim 13 wherein the system is integrable on board of an electric vehicle comprising an electric motor, and the heat generating component is the electric motor.

15. The system of claim 13 or 14 wherein the heat generating component is the/each magnetic field
25 source.

16. The system of any one of claims 8 to 15 wherein the thermal fluid is a liquid.

17. The system of claim 16 wherein the thermal fluid comprises magnetically susceptible additives agitable by the magnetic field produced by the one or more magnetic field sources.
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18. The system of claim 17 wherein the magnetically susceptible additives comprise ferromagnetic particles and/or filings and/or shavings.

35 19. The system of any one of claims 8-15 wherein the thermal fluid is a gas.

20. The system of any one of claims 8 to 19 wherein:
in use the one or more magnetic field sources are in thermal communication with the one or more electrochemical cells; and

40 the thermal management sub-system comprising a controller for controlling the magnetic field and a resulting amount of heat generated by the/each magnetic field source.

21. A system comprising:
a magneto-electrochemical sub-system comprising one or more magnetic field sources, the/each magnetic field source being configured to generate a respective magnetic field through one or more electrochemical cells; and
5 an electric motor electrically coupled to the magneto-electrochemical sub-system.
22. The system of claim 21 wherein the magneto-electrochemical sub-system is magnetically coupled to the electric motor via one or more magnetic field guides.
- 10 23. A system comprising:
a magneto-electrochemical sub-system comprising one or more magnetic field sources, the/each magnetic field source being configured to generate a respective magnetic field through one or more electrochemical cells;
one or more magnetic field guides; and
15 an electric motor magnetically coupled to the magneto-electrochemical sub-system via the one or more magnetic field guides.
24. The system of any preceding claim wherein at least one of the one or more electrochemical cells is in direct contact with at least one of the one or more magnetic field sources.
- 20 25. The system of any preceding claim wherein the magneto-electrochemical sub-system comprises the one or more electrochemical cells.
26. The system of claim 25, wherein the/each electrochemical cell is a Li-ion cell.
- 25 27. The system of any preceding claim wherein the/each magnetic field is a changing magnetic field.
28. An electric vehicle comprising the system of any one of the preceding claims.