Financial and Environmental Multi-Objective Optimisation of a Revenue-Stacking Solar+Battery Farm

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Supervisors: Dr. Richard G. A. Wills,
Dr. Andy J. Chipperfield

Contents

- Project Motivations
- Project Outline
- Evaluating Environmental Impacts
- Operating Strategy
- Results
- Further Work

Project Motivations

Deep decarbonisation requires **backup** power, and likely regular **curtailment** of renewable generation

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Backup today mostly from **coal** or **gas** plants

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Energy storage can do it instead, but is more expensive.

(McKenna et al., 2017)

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Grid batteries can make money by providing ancillary services, e.g. **frequency response**

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Some benefit from avoiding emissions of **spinning reserve**

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But this is small!

(Fripp, 2015)

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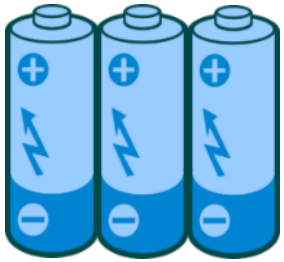
But this is small!

(Fripp, 2015)

Combine by **revenue stacking**.

Usually done to increase profit - why not environmental impact too?



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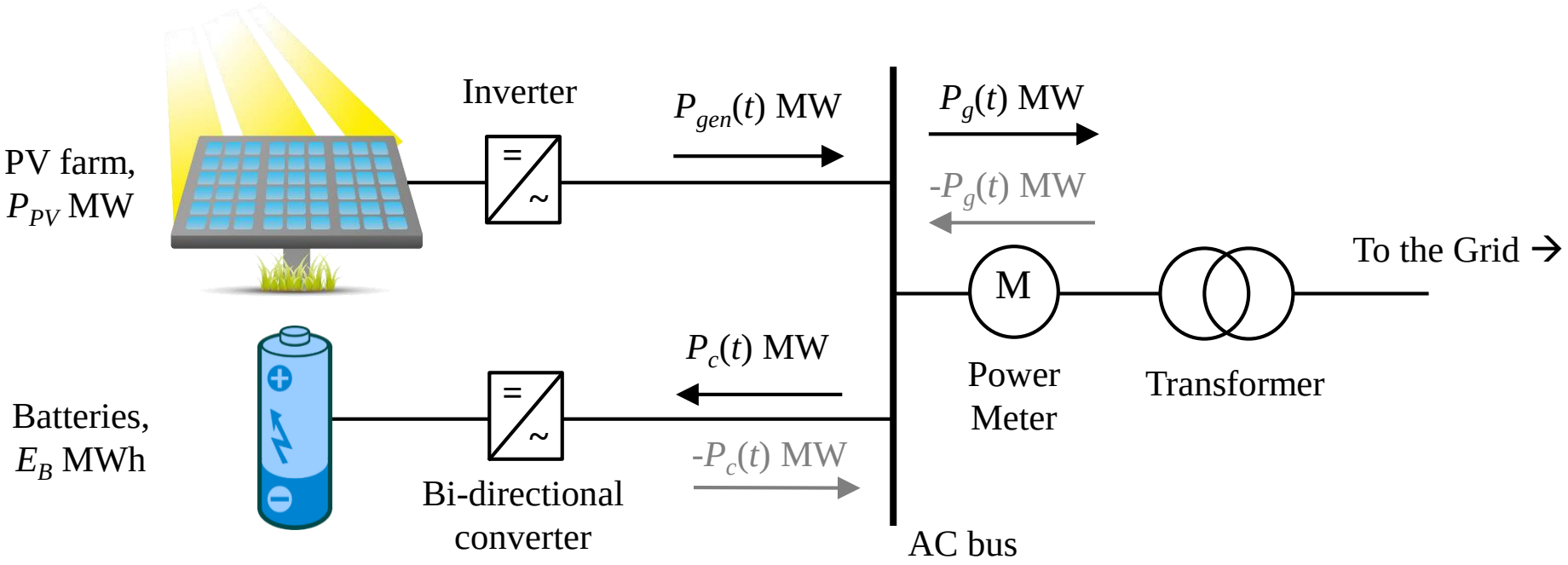
Project Outline

Behind-the-meter '**solar+**' PV-battery farm



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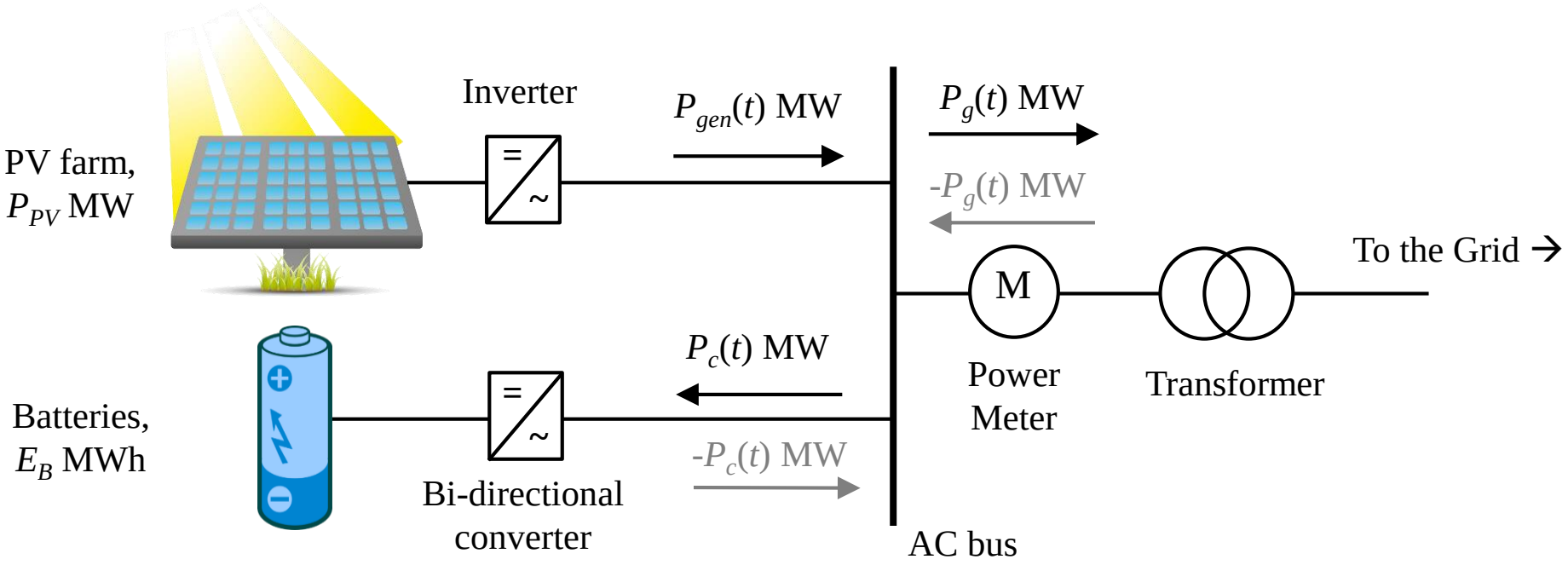

<u>Day mode</u>:
Trade electricity on the N2EX power exchange

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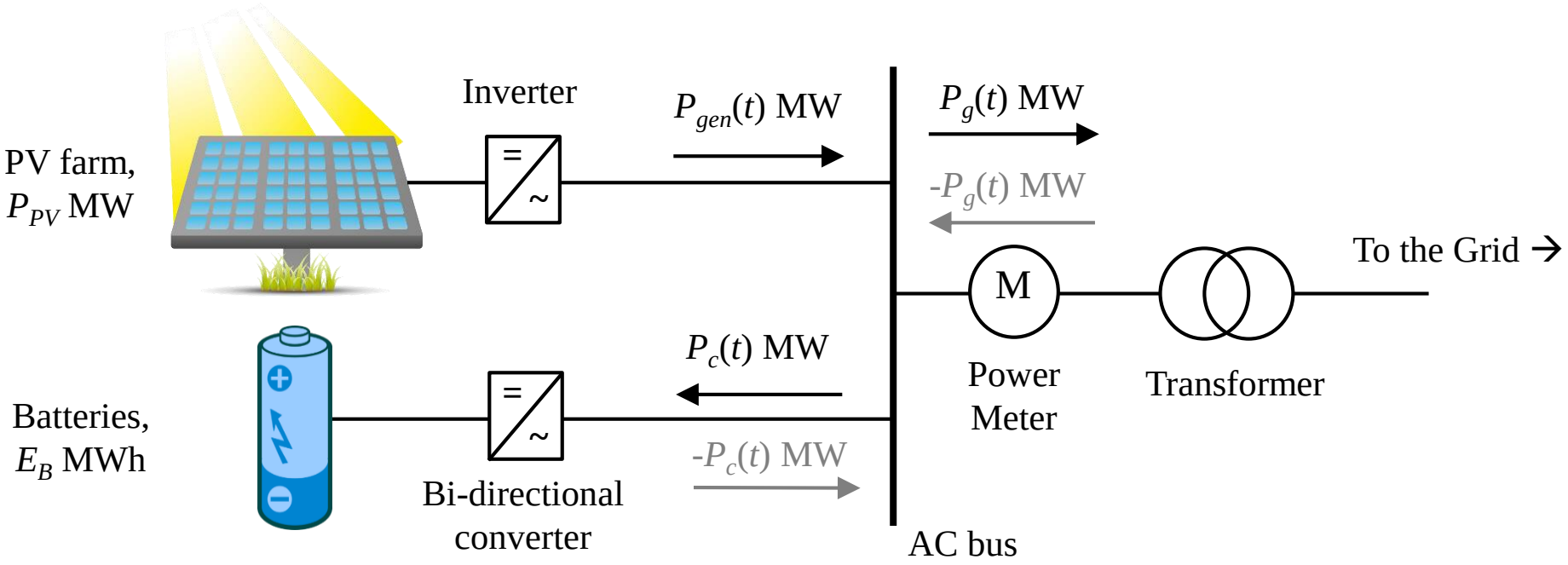

<u>Day mode</u>:
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Provide Enhanced Frequency Response (EFR)

Project Outline

Objectives:

- Internal Rate of Return
- + analogous expressions for environmental impacts

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Variables:

- PV capacity (MW)
- Battery capacity (MWh)
- Day-mode start time
- Day-mode end time

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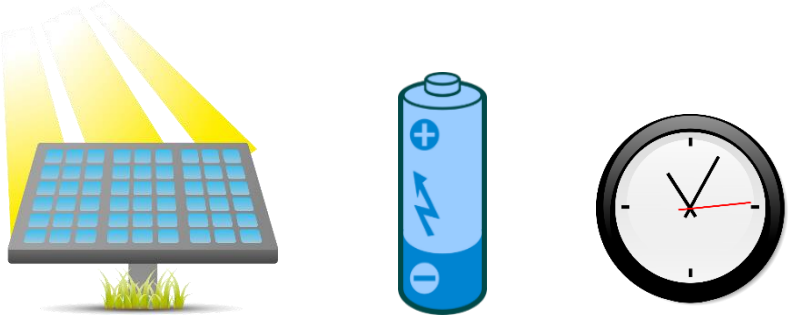
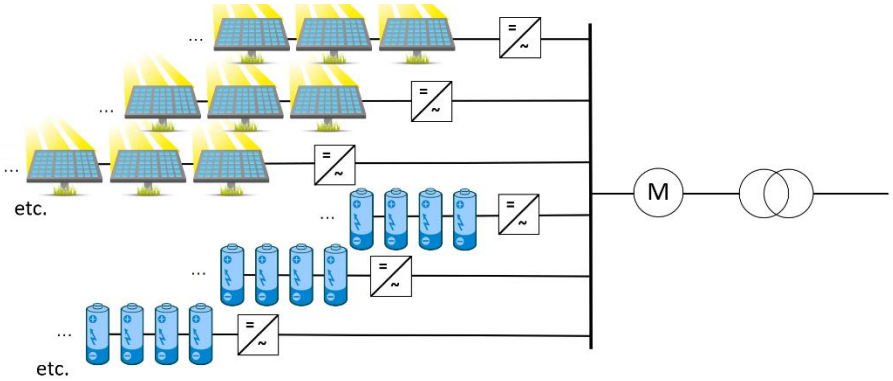


Variables:

- PV capacity (MW)
- Battery capacity (MWh)
- Day-mode start time
- Day-mode end time

Sensitivity Parameters:

- Battery type
- Component costs
- EFR payment
- Grid emissions scenarios
- Uncertainties in input data
- Imperfect forecasting
- etc. etc. etc.



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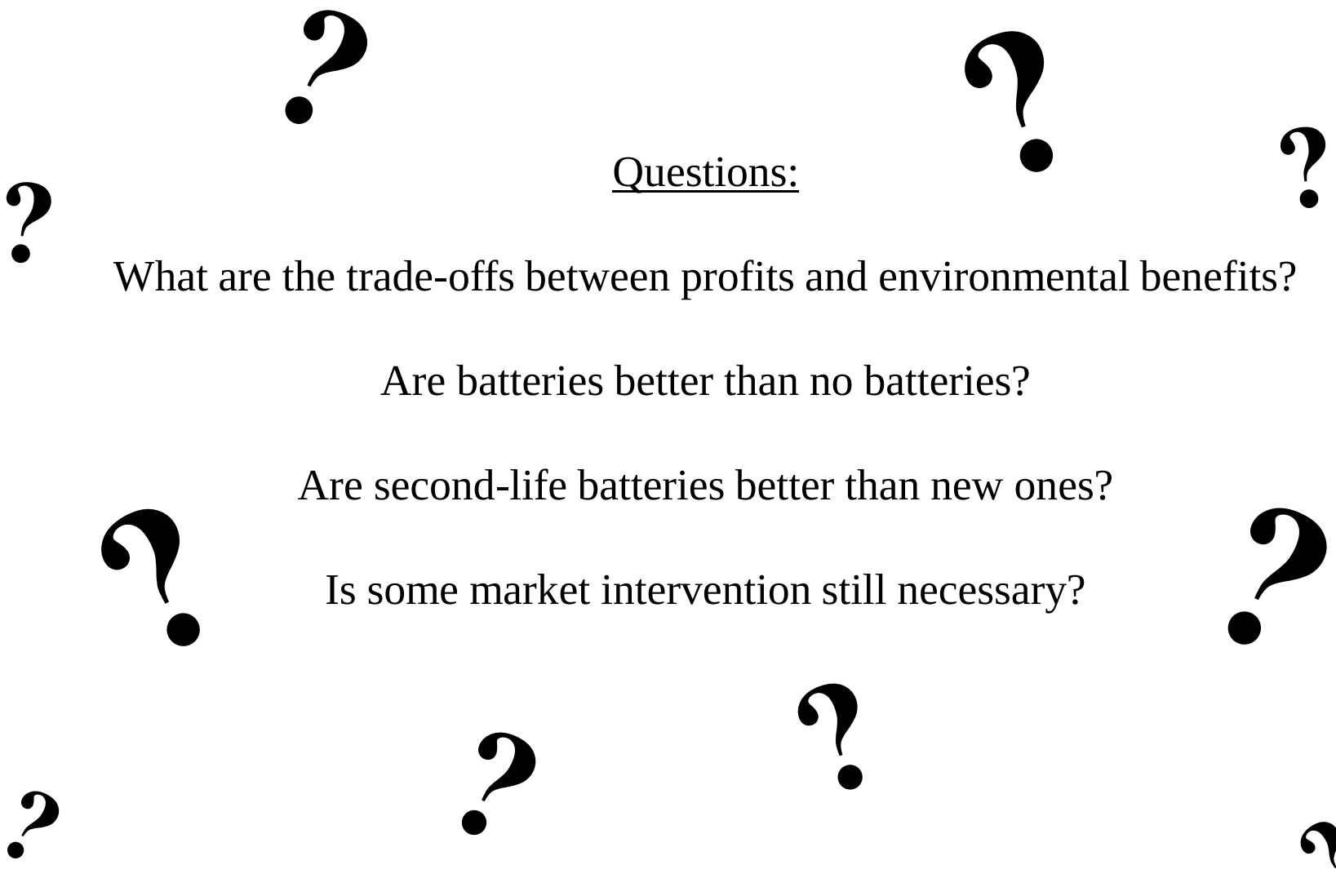

Questions:

What are the trade-offs between profits and environmental benefits?

Are batteries better than no batteries?

Are second-life batteries better than new ones?

Is some market intervention still necessary?

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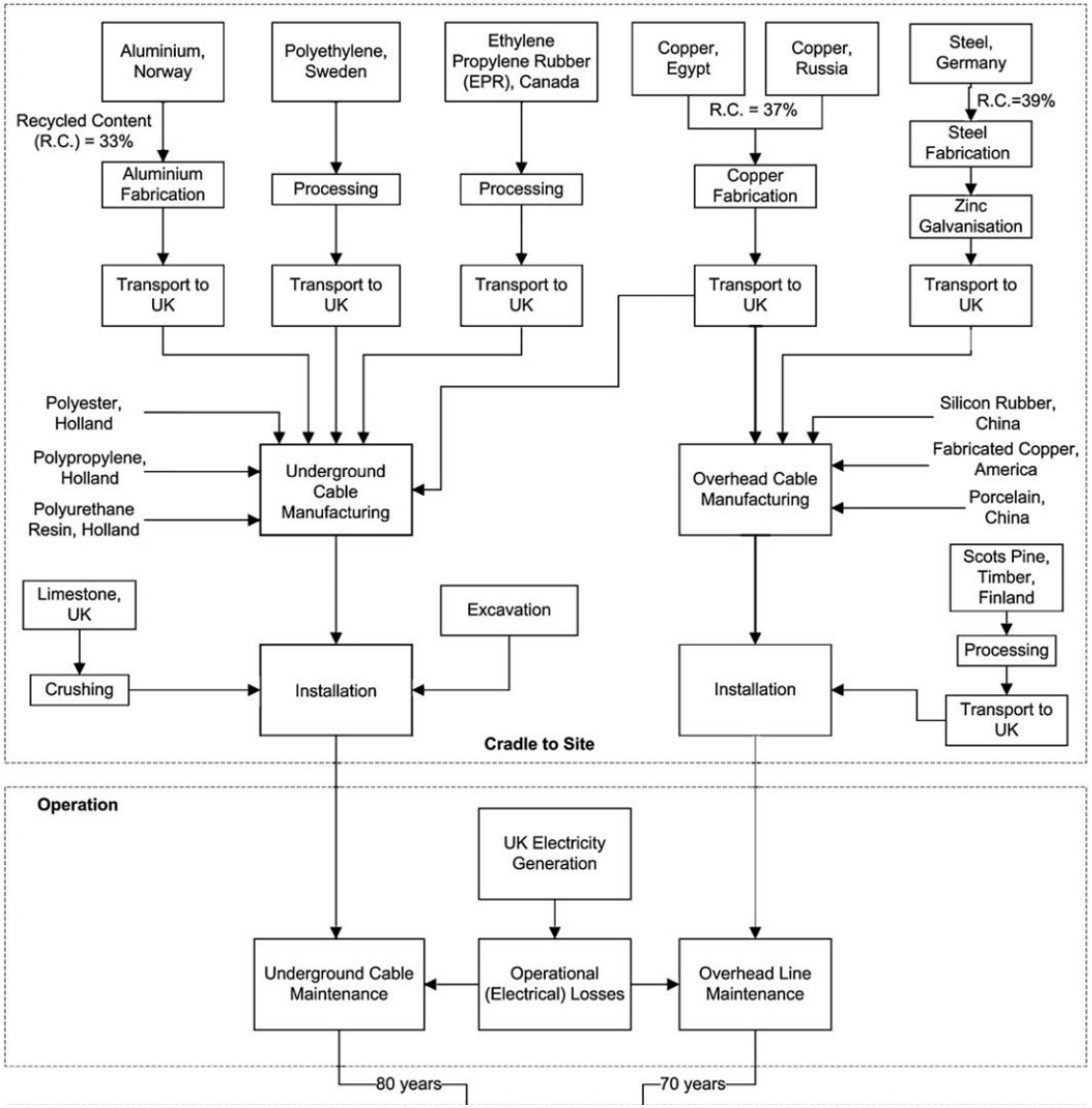
Evaluating Environmental Impacts

Life Cycle Analysis

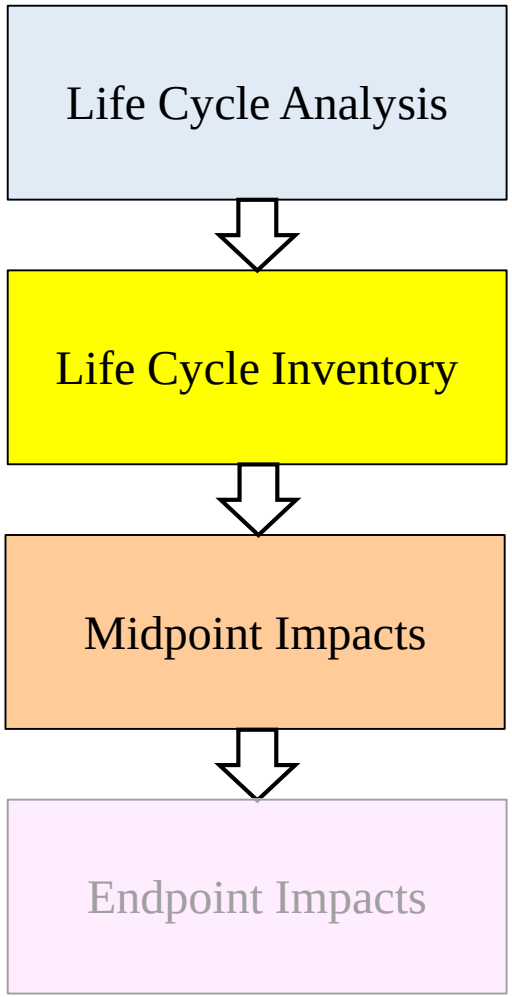
Life Cycle Inventory

Midpoint Impacts

Endpoint Impacts



Evaluating Environmental Impacts



ReCiPE

Climate Change……kg CO_2
Terrestrial Acidification……kg SO_2
Ozone Depletion……kg CFC-11
Photochemical Oxidant Formation……kg NO_x
Particulate Matter Formation……kg PM2.5
Human Toxicity……kg 1,4-DB
Ionising Radiation……..kBq Co-60
Ecotoxicity (Terrestrial, Freshwater, Marine)…kg 1,4-DB
Freshwater Eutrophication……kg P
Land Occupation (Natural, Agricultural)……..m^2.y
Natural Land Transformation……m^2
Water Depletion……..m^3
Minerals Depletion……kg Fe
Fossil Fuel Depletion……..kg oil

Evaluating Environmental Impacts

Life Cycle Analysis

↓

Life Cycle Inventory

↓

Midpoint Impacts

↓

Endpoint Impacts

Human Health
(DALY)

Natural Ecosystems
(species.y)

Natural Resources
(USD)

Evaluating Environmental Impacts

(Stamford and Azapagic, 2014)

(Hawkins et al., 2013)

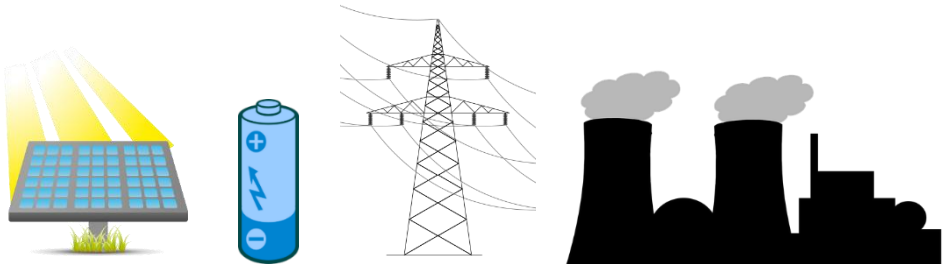
(McManus, 2012)

(Ellingsen et al., 2014)

(Palanov, 2014)

(Peters and Weil, 2017)

(Jones and McManus, 2010)



Self-portrait of the author

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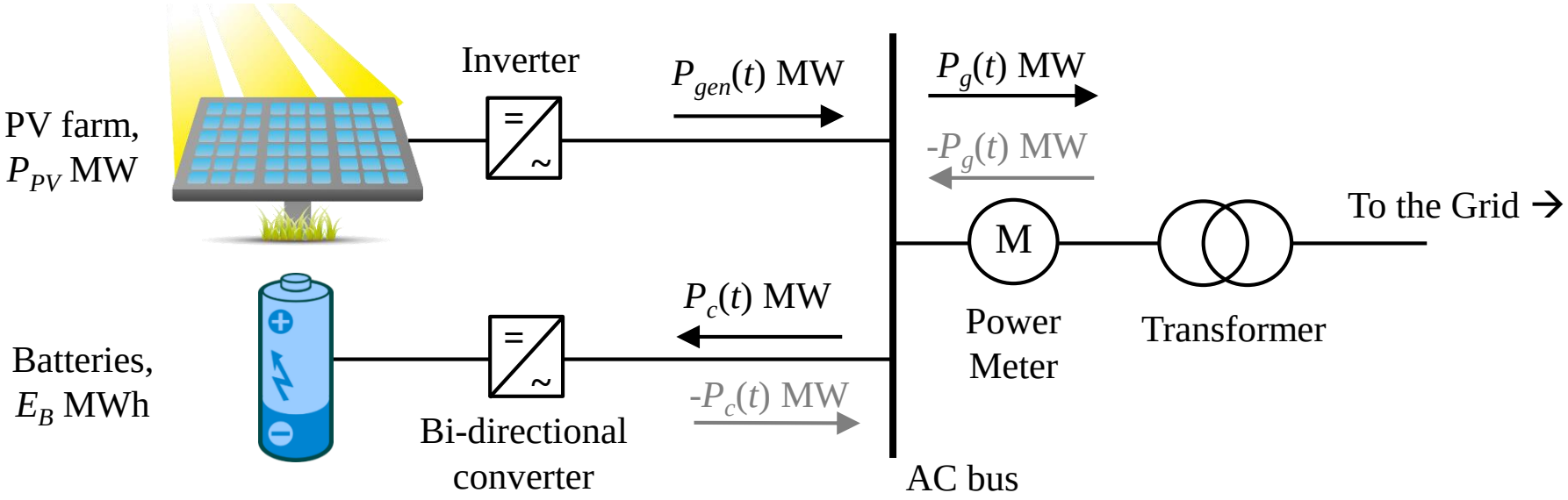
Operating Strategy – Linear Programming



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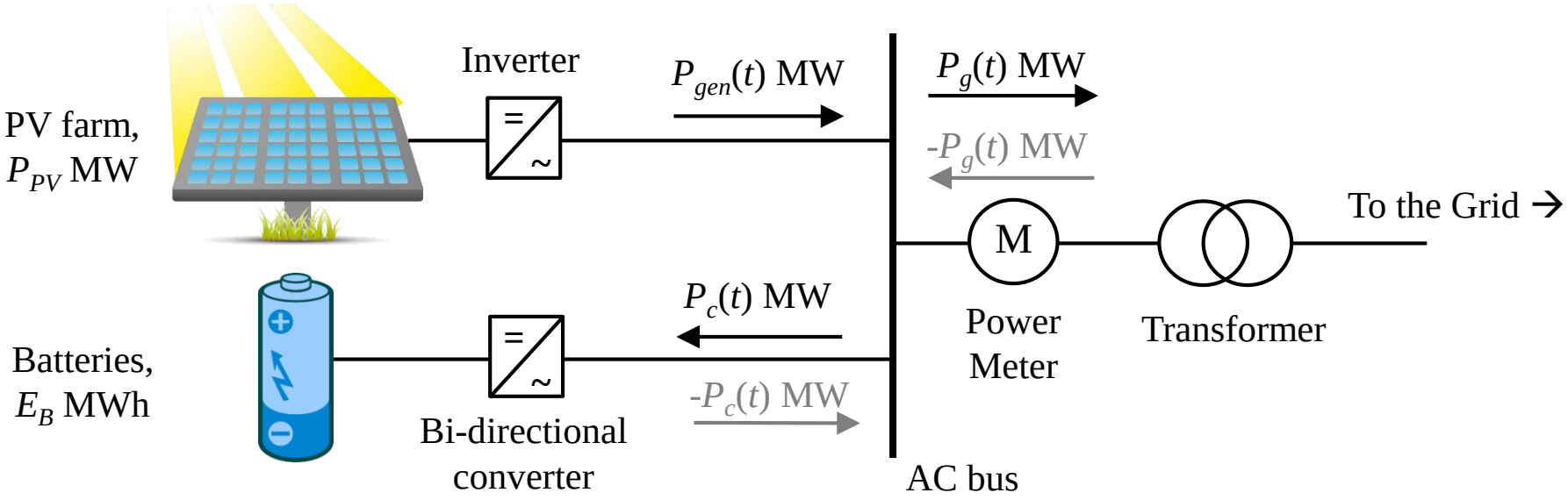
Night mode:
Provide Enhanced Frequency Response (EFR)

Operating Strategy – Linear Programming



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Objective: maximise day-ahead revenue

Variables: grid export and charging power

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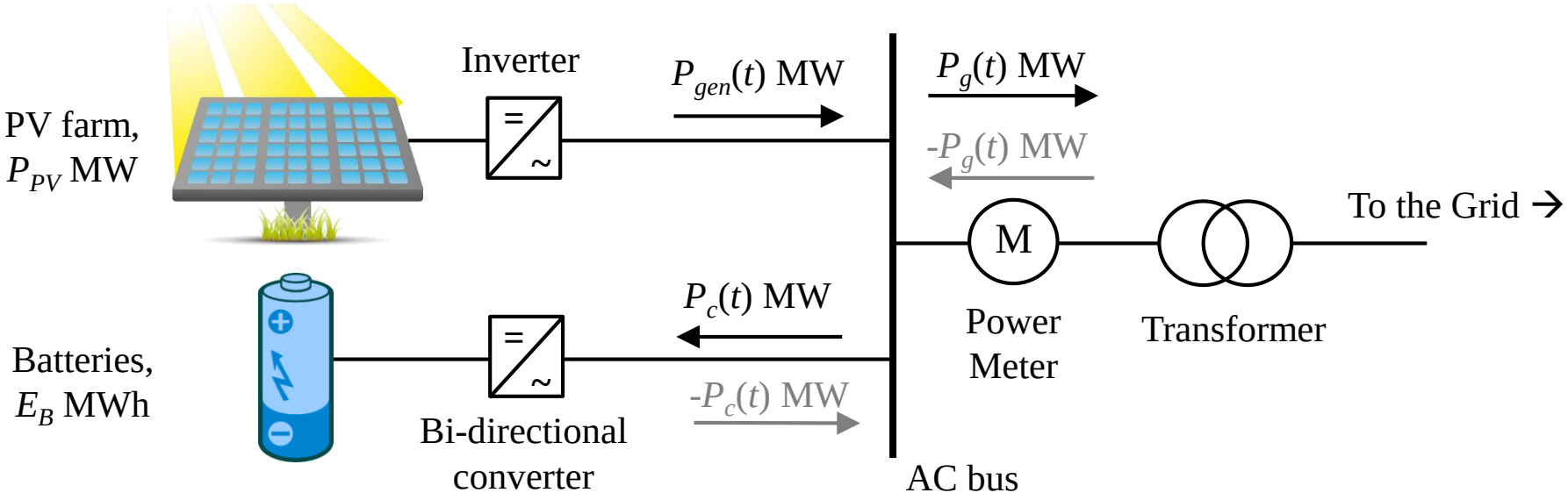

Day mode:
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Night mode:
Provide Enhanced Frequency Response (EFR)

Objective: maximise day-ahead revenue

Variables: grid export and charging power

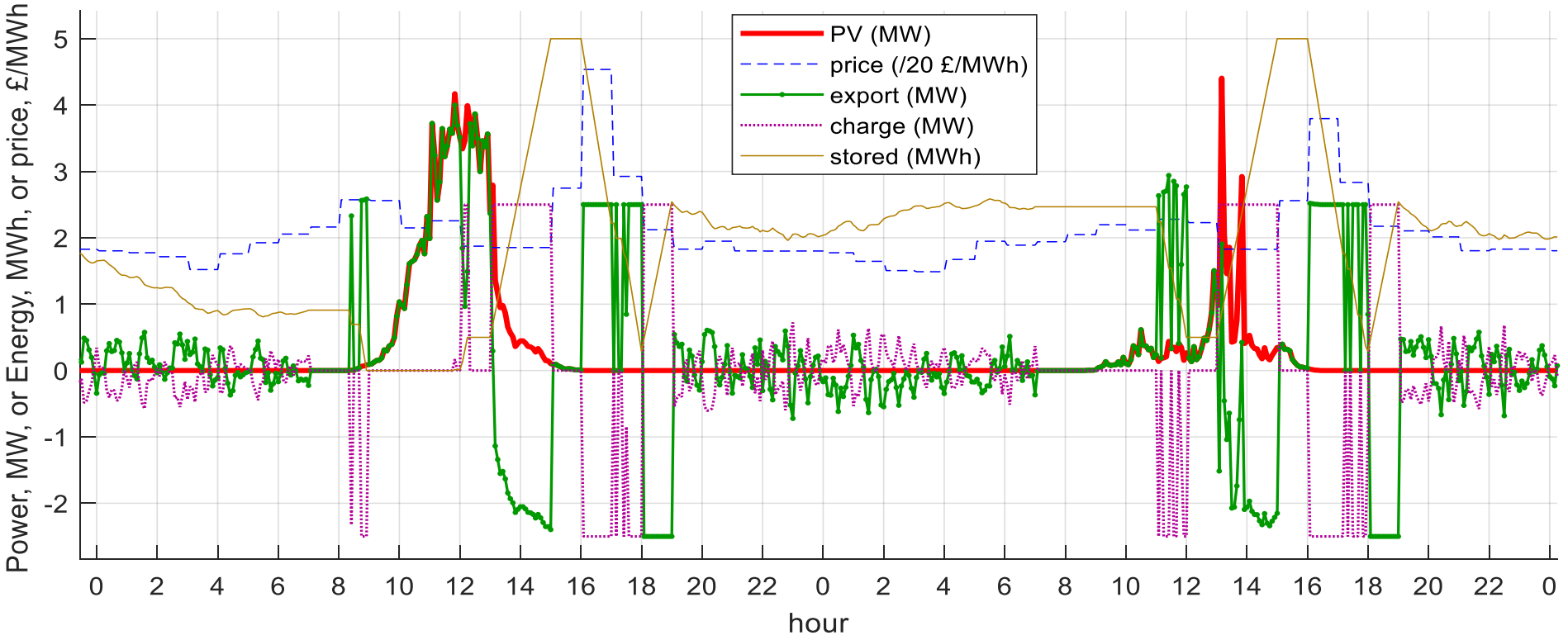
Constraints:

- Battery stored energy (low and high)
- Battery charge/discharge power
- Grid export limit
- Power balance (PV > export + charging)
- Time continuity of stored energy
- 'Foot-room' upon entering night mode

Operating Strategy – Scheduling Results

5-6th January

PV: **7.5 MW**; battery: **5.0 MWh**; charge/discharge limit: **2.5 MW**; grid import/export limit: **4.0 MW**; day mode: **07:00-19:00**



EFR in night-mode hours 19:00-07:00

Battery energy and power limits respected

Grid Export maximised at high-price periods

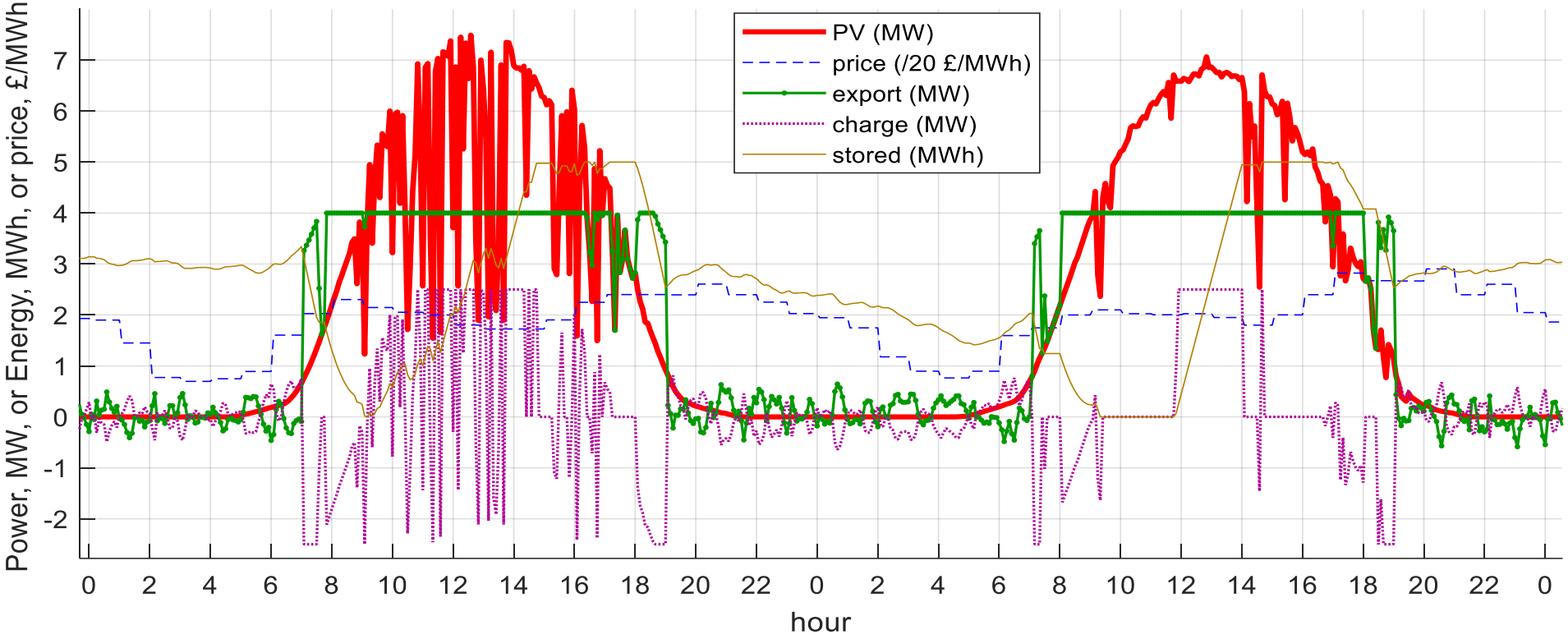
Import at low-price periods

Energy imported to fulfil foot-room required

Operating Strategy – Scheduling Results

5-6th June

PV: **7.5 MW**; battery: **5.0 MWh**; charge/discharge limit: **2.5 MW**; grid import/export limit: **4.0 MW**; day mode: **07:00-19:00**



EFR in night-mode hours 19:00-07:00

Battery energy and power limits respected

Grid Export capped at the limit 4.0 MW

Excess PV energy charges battery, within energy and power limits

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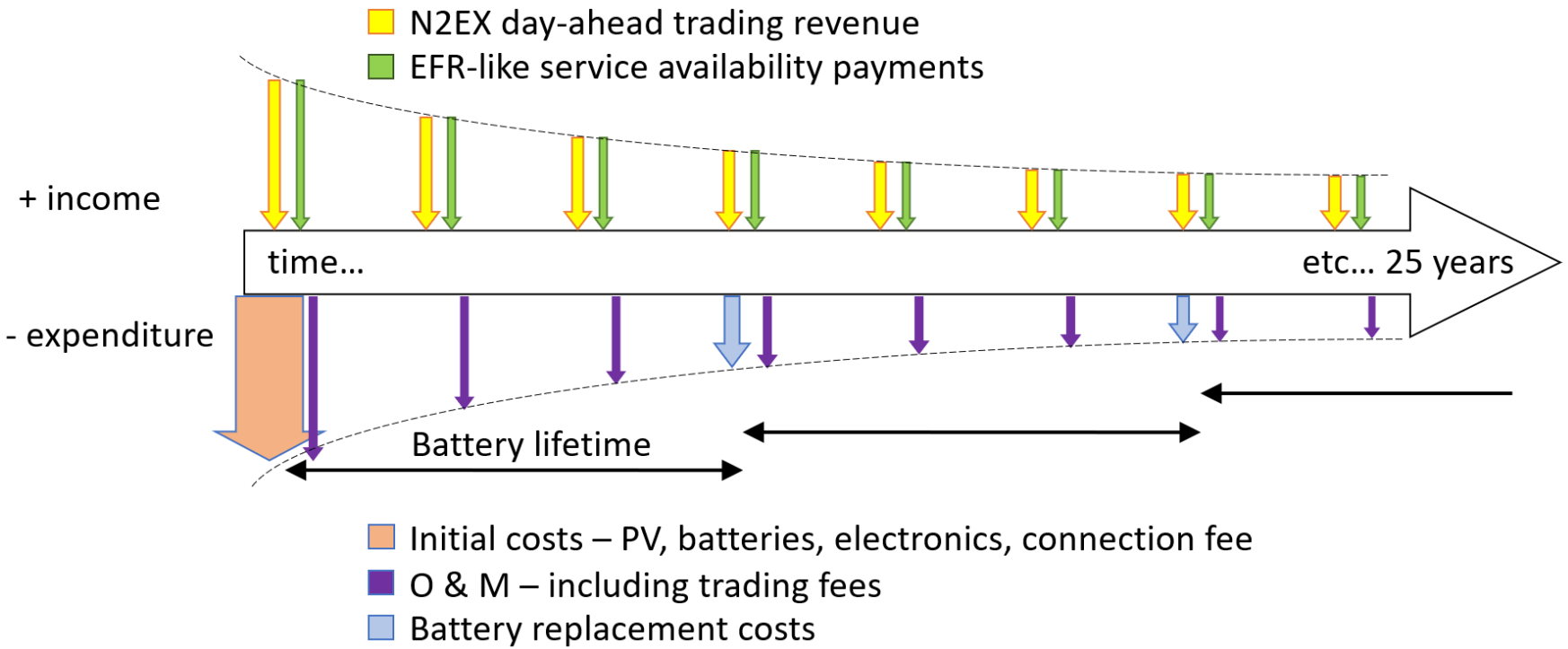
Results – Calculating NPV and IRR

Net Present Value: Incomes minus Expenditures, discounted by interest rate r_{int}

Internal Rate of Return: the value of r_{int} that makes NPV = 0

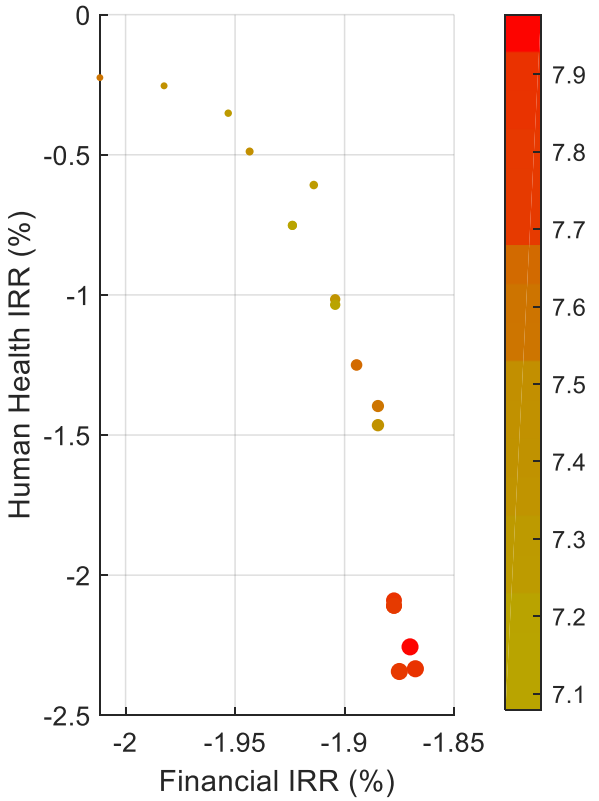


… and analogously for Human Health, Natural Ecosystems, and Natural Resources

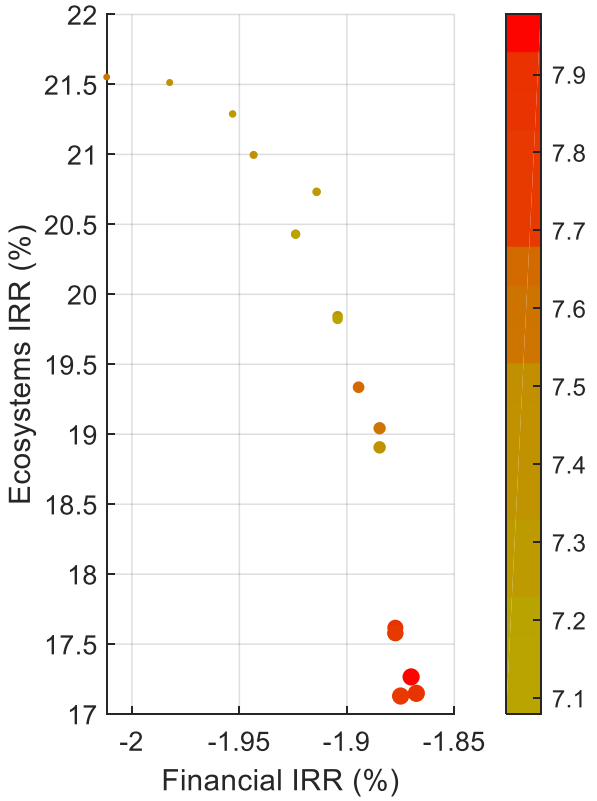
Results – Multi-Objective Pareto Fronts

Aqueous Na-ion battery; Population: 50; Generations: 50

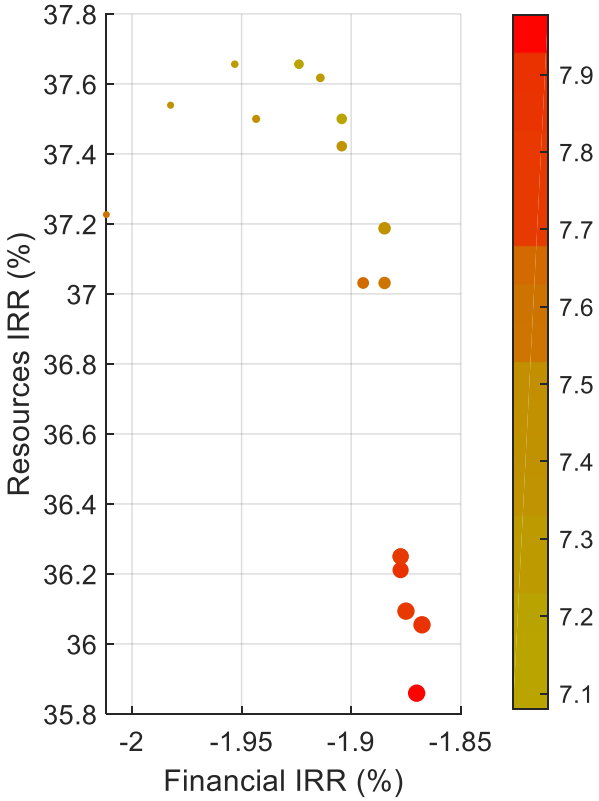
Human Health vs. Financial Return



Ecosystem Benefit vs. Financial Return



Resource Preservation vs. Financial Return



Day mode: **07:00-19:00** for all

PV: **7.1 MW** (yellow) – **8.0 MW** (red)

Battery: **2.2 MWh** (small marker) – **5.6 MWh** (large marker)

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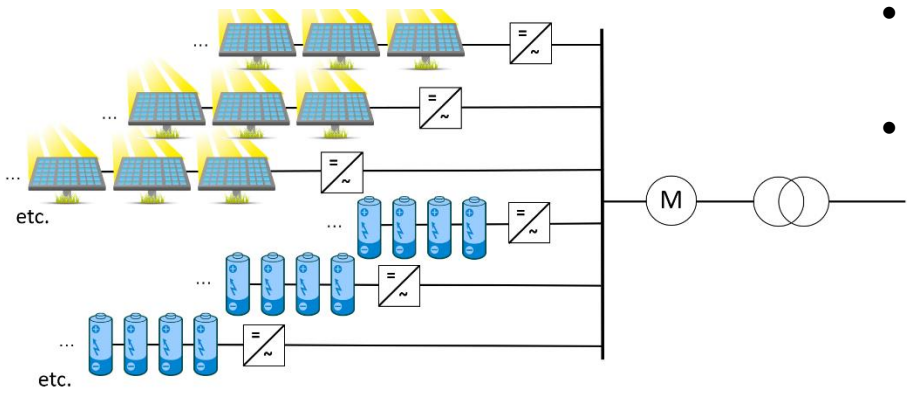

Grid Electricity:

- What are the environmental impacts of *marginal* grid generation?
- How do these vary throughout the day?
- How might they vary across the system lifetime?

Battery Modelling:

- How important are the Voltage-Current characteristics?
- Degradation of battery capacity and efficiency?
- Variation between cells? Packs? Modules?

Further Work

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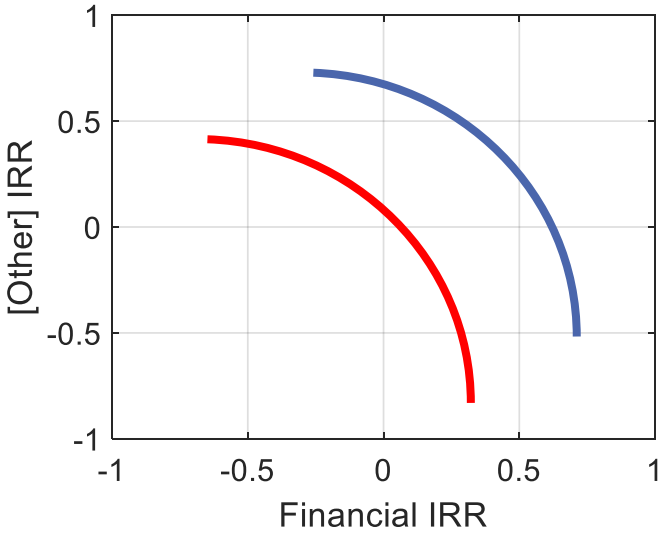
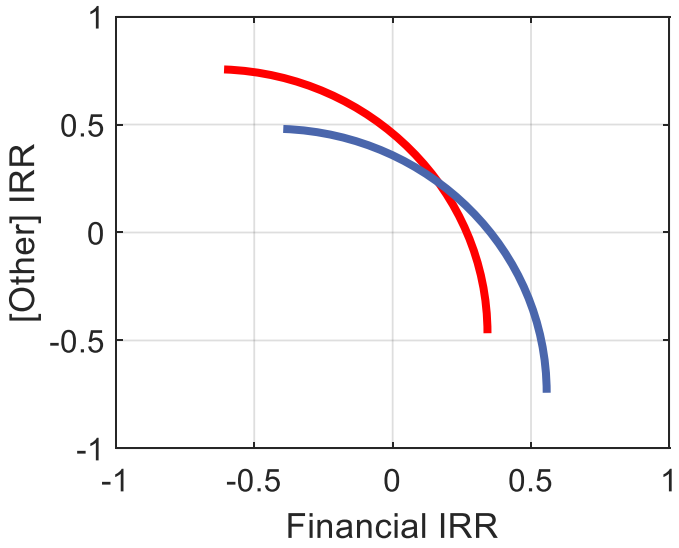


Fully dominating



Partially dominating

Thank you!