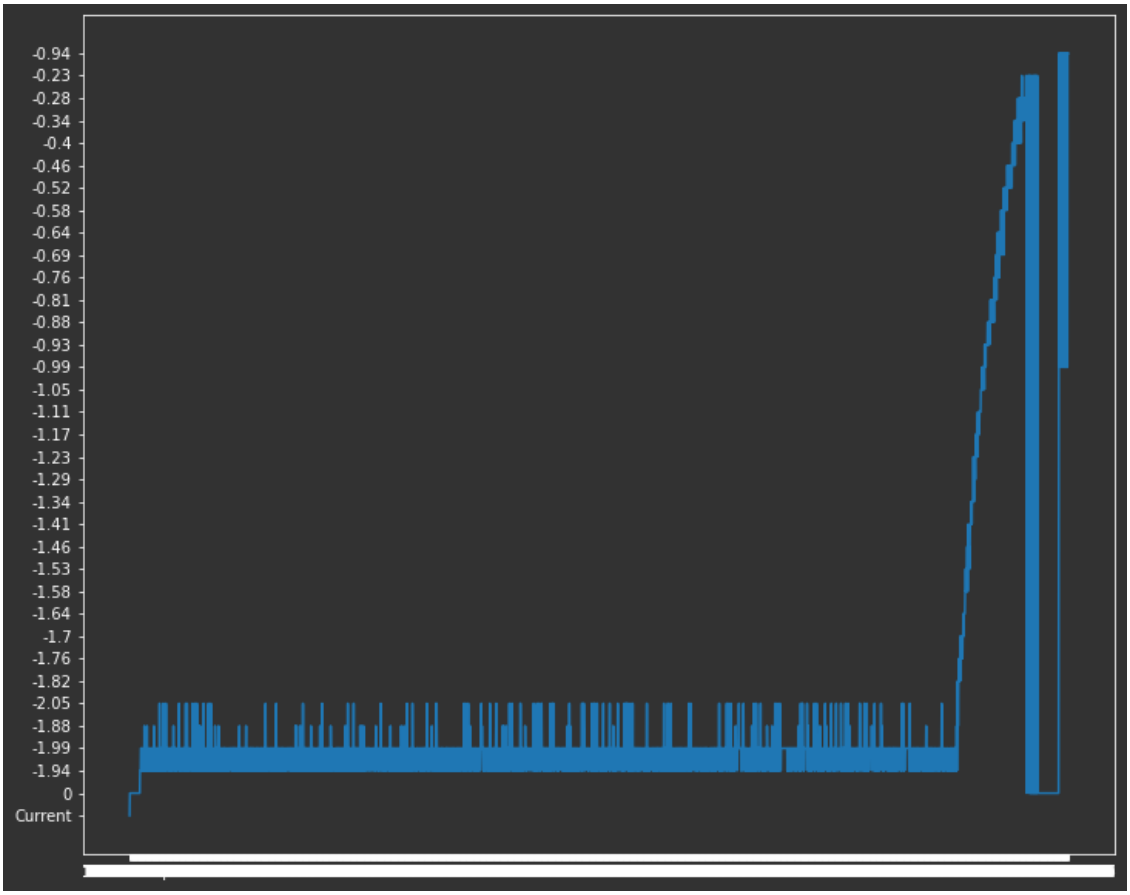
11P7S Thermal Simulation

August 31, 2022

[2]:
```
#Using Real time data
try:
    import liionpack as lp
except:
    !pip install -q git+https://github.com/pybamm-team/liionpack.git@main
    import liionpack as lp
import pybamm
import numpy as np
import os
import pandas as pd
import matplotlib.pyplot as plt

nproc = os.cpu_count()
os.chdir(pybamm.__path__[0] + "/..")
```

[3]:
```
# import Real time data from file
Real_time_data = pd.read_csv(r"C:\Users\Engineering\Desktop\Data Science/
 ↪Samsung-50E 7S11P.csv", comment="#",
                             header=None).to_numpy()
```

[4]:
```
# Current vs Time stamp graphical Analysis
with plt.rc_context(lp.lp_context()):
    plt.figure(figsize=(12, 10))
    plt.plot(Real_time_data[:, 0], Real_time_data[:, 1]) # The first column is␣
 ↪the time stamp and the second is the current.
```



[59]:
```
#Thermal Simulation : Overview of Simulation process and Steps
try:
    import liionpack as lp
except:
    !pip install -q git+https://github.com/pybamm-team/liionpack.git@main
    import liionpack as lp
import pybamm
import numpy as np
import inspect
lines = inspect.getsource(lp.thermal_simulation)
print(lines)
```

```
def thermal_simulation(parameter_values=None):
    """
    Create a PyBaMM simulation set up for integration with liionpack

    Args:
        parameter_values (pybamm.ParameterValues):
            The default is None.
```

```
    Returns:
        pybamm.Simulation:
            A simulation that can be solved individually or passed into the
            liionpack solve method

    """
    # Create the pybamm model
    model = pybamm.lithium_ion.SPMe(
        options={
            "thermal": "lumped",
            "timescale": tscale,
        }
    )

    # Add events to the model
    model = lp.add_events_to_model(model)

    # Set up parameter values
    if parameter_values is None:
        parameter_values = pybamm.ParameterValues("Chen2020")

    # Change the heat transfer coefficient to be an input controlled by the
    # external circuit
    parameter_values.update(
        {
            "Total heat transfer coefficient [W.m-2.K-1]": "[input]",
        },
    )

    # Set up solver and simulation
    solver = pybamm.CasadiSolver(mode="safe")
    sim = pybamm.Simulation(
        model=model,
        parameter_values=parameter_values,
        solver=solver,
    )
    return sim
```

[82]:
```
Np = 11
Ns = 7
I_mag = 2.0
Rsmall = 1e-6
OCV_init = 4.0
Nspm = Np * Ns
# Generate the netlist
```

```
netlist = lp.setup_circuit(Np=Np, Ns=Ns, Rb=Rsmall, Rc=Rsmall, Ri=3e-2,␣
 ↪I=I_mag, V=OCV_init)
# Define additional output variables
output_variables = [
    "Volume-averaged cell temperature [K]",
]
# Define a cycling experiment using PyBaMM
experiment = pybamm.Experiment(                                          ␣
 ↪#experiment for constant charge
    [
        "Charge at 2 A for 30 minutes",
        "Rest for 15 minutes",
        "Discharge at 2 A for 30 minutes",
        "Rest for 15 minutes",
     ]
    * 3,
    period="10 seconds",
)
experiment = pybamm.Experiment(                                          ␣
 ↪#experiment for constant discharge
    [
        (
        "Discharge at 2 A for 30 minutes",
        "Rest for 15 minutes",
        "Charge at 2 A for 30 minutes",
        "Rest for 15 minutes",
        )
    ]
    * 3,
    period="10 seconds",
)
# Define the PyBaMM parameters
parameter_Sets = pybamm.parameter_sets.Chen2020
parameter_values = pybamm.ParameterValues("Chen2020")
parameter_values.update(
    {"Total heat transfer coefficient [W.m-2.K-1]": "[input]"}
)
htc = np.random.random(Nspm) * 50.0
inputs = {"Total heat transfer coefficient [W.m-2.K-1]": htc}
# Solve the pack
output = lp.solve(
    netlist=netlist,
    sim_func=lp.thermal_simulation,
    parameter_values=parameter_values,
    experiment=experiment,
    output_variables=output_variables,
    inputs=inputs,
```

```
    initial_soc=0.5,
    nproc=nproc
)
```

```
Stepping simulation: 100%|      | 1621/1621 [01:21<00:00, 19.85it/s]
```

[40]:
```
parameter_Sets
```

[40]:
```
{'chemistry': 'lithium_ion',
 'cell': 'LGM50_Chen2020',
 'negative electrode': 'graphite_Chen2020',
 'separator': 'separator_Chen2020',
 'positive electrode': 'nmc_Chen2020',
 'electrolyte': 'lipf6_Nyman2008',
 'experiment': '1C_discharge_from_full_Chen2020',
 'sei': 'example',
 'citation': 'Chen2020'}
```

[41]:
```
parameter_values
```

[41]:
```
{'1 + dlnf/dlnc': 1.0,
 'Ambient temperature [K]': 298.15,
 'Bulk solvent concentration [mol.m-3]': 2636.0,
 'Cation transference number': 0.2594,
 'Cell cooling surface area [m2]': 0.00531,
 'Cell thermal expansion coefficient [m.K-1]': 1.1e-06,
 'Cell volume [m3]': 2.42e-05,
 'Current function [A]': InputParameter(-0x315cd1d7bccdd3e0, Current function
[A], children=[], domains={}),
 'EC diffusivity [m2.s-1]': 2e-18,
 'EC initial concentration in electrolyte [mol.m-3]': 4541.0,
 'Electrode height [m]': 0.065,
 'Electrode width [m]': 1.58,
 'Electrolyte conductivity [S.m-1]': <function
electrolyte_conductivity_Nyman2008 at 0x0000024F4D411670>,
 'Electrolyte diffusivity [m2.s-1]': <function electrolyte_diffusivity_Nyman2008
at 0x0000024F5CB2A280>,
 'Initial concentration in electrolyte [mol.m-3]': 1000.0,
 'Initial concentration in negative electrode [mol.m-3]': 15522.13824903797,
 'Initial concentration in positive electrode [mol.m-3]': 35269.54644322063,
 'Initial inner SEI thickness [m]': 2.5e-09,
 'Initial outer SEI thickness [m]': 2.5e-09,
 'Initial temperature [K]': 298.15,
 'Inner SEI electron conductivity [S.m-1]': 8.95e-14,
 'Inner SEI lithium interstitial diffusivity [m2.s-1]': 1e-20,
 'Inner SEI open-circuit potential [V]': 0.1,
 'Inner SEI partial molar volume [m3.mol-1]': 9.585e-05,
 'Inner SEI reaction proportion': 0.5,
```

```
 'Lithium interstitial reference concentration [mol.m-3]': 15.0,
 'Lower voltage cut-off [V]': 2.5,
 'Maximum concentration in negative electrode [mol.m-3]': 33133.0,
 'Maximum concentration in positive electrode [mol.m-3]': 63104.0,
 'Negative current collector conductivity [S.m-1]': 58411000.0,
 'Negative current collector density [kg.m-3]': 8960.0,
 'Negative current collector specific heat capacity [J.kg-1.K-1]': 385.0,
 'Negative current collector thermal conductivity [W.m-1.K-1]': 401.0,
 'Negative current collector thickness [m]': 1.2e-05,
 'Negative electrode Bruggeman coefficient (electrode)': 1.5,
 'Negative electrode Bruggeman coefficient (electrolyte)': 1.5,
 'Negative electrode OCP [V]': <function graphite_LGM50_ocp_Chen2020 at
0x0000024F4D411E50>,
 'Negative electrode OCP entropic change [V.K-1]': 0.0,
 'Negative electrode active material volume fraction': 0.75,
 'Negative electrode cation signed stoichiometry': -1.0,
 'Negative electrode charge transfer coefficient': 0.5,
 'Negative electrode conductivity [S.m-1]': 215.0,
 'Negative electrode density [kg.m-3]': 1657.0,
 'Negative electrode diffusivity [m2.s-1]': 3.3e-14,
 'Negative electrode double-layer capacity [F.m-2]': 0.2,
 'Negative electrode electrons in reaction': 1.0,
 'Negative electrode exchange-current density [A.m-2]': <function
graphite_LGM50_electrolyte_exchange_current_density_Chen2020 at
0x0000024F571730D0>,
 'Negative electrode porosity': 0.25,
 'Negative electrode reaction-driven LAM factor [m3.mol-1]': 0.0,
 'Negative electrode specific heat capacity [J.kg-1.K-1]': 700.0,
 'Negative electrode thermal conductivity [W.m-1.K-1]': 1.7,
 'Negative electrode thickness [m]': 8.52e-05,
 'Negative particle radius [m]': 5.86e-06,
 'Nominal cell capacity [A.h]': 5.0,
 'Number of cells connected in series to make a battery': 1.0,
 'Number of electrodes connected in parallel to make a cell': 1.0,
 'Outer SEI open-circuit potential [V]': 0.8,
 'Outer SEI partial molar volume [m3.mol-1]': 9.585e-05,
 'Outer SEI solvent diffusivity [m2.s-1]': 2.5000000000000002e-22,
 'Positive current collector conductivity [S.m-1]': 36914000.0,
 'Positive current collector density [kg.m-3]': 2700.0,
 'Positive current collector specific heat capacity [J.kg-1.K-1]': 897.0,
 'Positive current collector thermal conductivity [W.m-1.K-1]': 237.0,
 'Positive current collector thickness [m]': 1.6e-05,
 'Positive electrode Bruggeman coefficient (electrode)': 1.5,
 'Positive electrode Bruggeman coefficient (electrolyte)': 1.5,
 'Positive electrode OCP [V]': <function nmc_LGM50_ocp_Chen2020 at
0x0000024F56FB6AF0>,
 'Positive electrode OCP entropic change [V.K-1]': 0.0,
```

```
 'Positive electrode active material volume fraction': 0.665,
 'Positive electrode cation signed stoichiometry': -1.0,
 'Positive electrode charge transfer coefficient': 0.5,
 'Positive electrode conductivity [S.m-1]': 0.18,
 'Positive electrode density [kg.m-3]': 3262.0,
 'Positive electrode diffusivity [m2.s-1]': 4e-15,
 'Positive electrode double-layer capacity [F.m-2]': 0.2,
 'Positive electrode electrons in reaction': 1.0,
 'Positive electrode exchange-current density [A.m-2]': <function
nmc_LGM50_electrolyte_exchange_current_density_Chen2020 at 0x0000024F56FB6550>,
 'Positive electrode porosity': 0.335,
 'Positive electrode reaction-driven LAM factor [m3.mol-1]': 0.0,
 'Positive electrode specific heat capacity [J.kg-1.K-1]': 700.0,
 'Positive electrode thermal conductivity [W.m-1.K-1]': 2.1,
 'Positive electrode thickness [m]': 7.56e-05,
 'Positive particle radius [m]': 5.22e-06,
 'Reference temperature [K]': 298.15,
 'SEI growth activation energy [J.mol-1]': 0.0,
 'SEI kinetic rate constant [m.s-1]': 1e-12,
 'SEI open-circuit potential [V]': 0.4,
 'SEI reaction exchange current density [A.m-2]': 1.5e-07,
 'SEI resistivity [Ohm.m]': 200000.0,
 'Separator Bruggeman coefficient (electrolyte)': 1.5,
 'Separator density [kg.m-3]': 397.0,
 'Separator porosity': 0.47,
 'Separator specific heat capacity [J.kg-1.K-1]': 700.0,
 'Separator thermal conductivity [W.m-1.K-1]': 0.16,
 'Separator thickness [m]': 1.2e-05,
 'Total heat transfer coefficient [W.m-2.K-1]':
InputParameter(-0x3b73eced6b52d0c9, Total heat transfer coefficient [W.m-2.K-1],
children=[], domains={}),
 'Typical current [A]': 5.0,
 'Typical electrolyte concentration [mol.m-3]': 1000.0,
 'Upper voltage cut-off [V]': 4.2}
```

[42]:
```
experiment.operating_conditions   # View the experiment steps
```

[42]:
```
[{'electric': (2.0, 'A'), 'time': 1800.0, 'period': 10.0, 'dc_data': None},
 {'electric': (0, 'A'), 'time': 900.0, 'period': 10.0, 'dc_data': None},
 {'electric': (-2.0, 'A'), 'time': 1800.0, 'period': 10.0, 'dc_data': None},
 {'electric': (0, 'A'), 'time': 900.0, 'period': 10.0, 'dc_data': None},
 {'electric': (2.0, 'A'), 'time': 1800.0, 'period': 10.0, 'dc_data': None},
 {'electric': (0, 'A'), 'time': 900.0, 'period': 10.0, 'dc_data': None},
 {'electric': (-2.0, 'A'), 'time': 1800.0, 'period': 10.0, 'dc_data': None},
 {'electric': (0, 'A'), 'time': 900.0, 'period': 10.0, 'dc_data': None},
 {'electric': (2.0, 'A'), 'time': 1800.0, 'period': 10.0, 'dc_data': None},
 {'electric': (0, 'A'), 'time': 900.0, 'period': 10.0, 'dc_data': None},
```

```
 {'electric': (-2.0, 'A'), 'time': 1800.0, 'period': 10.0, 'dc_data': None},
 {'electric': (0, 'A'), 'time': 900.0, 'period': 10.0, 'dc_data': None}]
```

[43]:
```
# The default included data is the 'Cell current [A]','Terminal voltage
 ↪[V]',and 'Measured battery open circuit voltage [V]'.
SPMe = pybamm.models.full_battery_models.lithium_ion.SPMe()
SPMe.variable_names()
```

[43]:
```
['Time',
 'Time [s]',
 'Time [min]',
 'Time [h]',
 'x',
 'x [m]',
 'x_n',
 'x_n [m]',
 'x_s',
 'x_s [m]',
 'x_p',
 'x_p [m]',
 'r_p',
 'r_p [m]',
 'r_n',
 'r_n [m]',
 'Current density variable',
 'Total current density',
 'Total current density [A.m-2]',
 'Current [A]',
 'C-rate',
 'Discharge capacity [A.h]',
 'Porosity',
 'Separator porosity',
 'Positive electrode porosity',
 'X-averaged separator porosity',
 'X-averaged positive electrode porosity',
 'Negative electrode porosity',
 'X-averaged negative electrode porosity',
 'Leading-order porosity',
 'Leading-order separator porosity',
 'Leading-order positive electrode porosity',
 'Leading-order x-averaged separator porosity',
 'Leading-order x-averaged positive electrode porosity',
 'Leading-order negative electrode porosity',
 'Leading-order x-averaged negative electrode porosity',
 'Porosity change',
 'Separator porosity change',
 'Positive electrode porosity change',
```

```
'X-averaged separator porosity change',
'X-averaged positive electrode porosity change',
'Negative electrode porosity change',
'X-averaged negative electrode porosity change',
'Leading-order x-averaged separator porosity change',
'Leading-order x-averaged positive electrode porosity change',
'Leading-order x-averaged negative electrode porosity change',
'Negative electrode interface utilisation variable',
'X-averaged negative electrode interface utilisation variable',
'Negative electrode interface utilisation',
'X-averaged negative electrode interface utilisation',
'Positive electrode interface utilisation variable',
'X-averaged positive electrode interface utilisation variable',
'Positive electrode interface utilisation',
'X-averaged positive electrode interface utilisation',
'Negative particle crack length [m]',
'Negative particle crack length',
'X-averaged negative particle crack length',
'X-averaged negative particle crack length [m]',
'Negative particle cracking rate',
'X-averaged Negative particle cracking rate',
'Positive particle crack length [m]',
'Positive particle crack length',
'X-averaged positive particle crack length',
'X-averaged positive particle crack length [m]',
'Positive particle cracking rate',
'X-averaged Positive particle cracking rate',
'Negative electrode active material volume fraction',
'X-averaged negative electrode active material volume fraction',
'Negative electrode capacity [A.h]',
'Negative particle radius',
'Negative particle radius [m]',
'Negative electrode surface area to volume ratio',
'Negative electrode surface area to volume ratio [m-1]',
'X-averaged negative electrode surface area to volume ratio',
'X-averaged negative electrode surface area to volume ratio [m-1]',
'Negative electrode active material volume fraction change',
'X-averaged negative electrode active material volume fraction change',
'Positive electrode active material volume fraction',
'X-averaged positive electrode active material volume fraction',
'Positive electrode capacity [A.h]',
'Positive particle radius',
'Positive particle radius [m]',
'Positive electrode surface area to volume ratio',
'Positive electrode surface area to volume ratio [m-1]',
'X-averaged positive electrode surface area to volume ratio',
'X-averaged positive electrode surface area to volume ratio [m-1]',
```

```
 'Positive electrode active material volume fraction change',
 'X-averaged positive electrode active material volume fraction change',
 'Positive electrode volume-averaged velocity',
 'Positive electrode volume-averaged velocity [m.s-1]',
 'Negative electrode volume-averaged velocity',
 'Negative electrode volume-averaged velocity [m.s-1]',
 'Positive electrode volume-averaged acceleration',
 'Positive electrode volume-averaged acceleration [m.s-1]',
 'X-averaged positive electrode volume-averaged acceleration',
 'X-averaged positive electrode volume-averaged acceleration [m.s-1]',
 'Negative electrode volume-averaged acceleration',
 'Negative electrode volume-averaged acceleration [m.s-1]',
 'X-averaged negative electrode volume-averaged acceleration',
 'X-averaged negative electrode volume-averaged acceleration [m.s-1]',
 'Positive electrode pressure',
 'X-averaged positive electrode pressure',
 'Negative electrode pressure',
 'X-averaged negative electrode pressure',
 'Separator pressure',
 'X-averaged separator pressure',
 'Separator transverse volume-averaged velocity',
 'Positive electrode transverse volume-averaged velocity',
 'Separator transverse volume-averaged velocity [m.s-2]',
 'Positive electrode transverse volume-averaged velocity [m.s-2]',
 'X-averaged separator transverse volume-averaged velocity',
 'X-averaged positive electrode transverse volume-averaged velocity',
 'X-averaged separator transverse volume-averaged velocity [m.s-2]',
 'X-averaged positive electrode transverse volume-averaged velocity [m.s-2]',
 'Transverse volume-averaged velocity',
 'Transverse volume-averaged velocity [m.s-2]',
 'Negative electrode transverse volume-averaged velocity',
 'Negative electrode transverse volume-averaged velocity [m.s-2]',
 'X-averaged negative electrode transverse volume-averaged velocity',
 'X-averaged negative electrode transverse volume-averaged velocity [m.s-2]',
 'Separator transverse volume-averaged acceleration',
 'Positive electrode transverse volume-averaged acceleration',
 'Separator transverse volume-averaged acceleration [m.s-2]',
 'Positive electrode transverse volume-averaged acceleration [m.s-2]',
 'X-averaged separator transverse volume-averaged acceleration',
 'X-averaged positive electrode transverse volume-averaged acceleration',
 'X-averaged separator transverse volume-averaged acceleration [m.s-2]',
 'X-averaged positive electrode transverse volume-averaged acceleration
[m.s-2]',
 'Transverse volume-averaged acceleration',
 'Transverse volume-averaged acceleration [m.s-2]',
 'Negative electrode transverse volume-averaged acceleration',
 'Negative electrode transverse volume-averaged acceleration [m.s-2]',
```

```
 'X-averaged negative electrode transverse volume-averaged acceleration',
 'X-averaged negative electrode transverse volume-averaged acceleration
[m.s-2]',
 'Negative particle concentration',
 'Negative particle concentration [mol.m-3]',
 'X-averaged negative particle concentration',
 'X-averaged negative particle concentration [mol.m-3]',
 'R-averaged negative particle concentration',
 'R-averaged negative particle concentration [mol.m-3]',
 'Average negative particle concentration',
 'Average negative particle concentration [mol.m-3]',
 'Negative particle surface concentration',
 'Negative particle surface concentration [mol.m-3]',
 'X-averaged negative particle surface concentration',
 'X-averaged negative particle surface concentration [mol.m-3]',
 'Negative electrode extent of lithiation',
 'X-averaged negative electrode extent of lithiation',
 'Minimum negative particle concentration',
 'Maximum negative particle concentration',
 'Minimum negative particle concentration [mol.m-3]',
 'Maximum negative particle concentration [mol.m-3]',
 'Minimum negative particle surface concentration',
 'Maximum negative particle surface concentration',
 'Minimum negative particle surface concentration [mol.m-3]',
 'Maximum negative particle surface concentration [mol.m-3]',
 'Positive particle concentration',
 'Positive particle concentration [mol.m-3]',
 'X-averaged positive particle concentration',
 'X-averaged positive particle concentration [mol.m-3]',
 'R-averaged positive particle concentration',
 'R-averaged positive particle concentration [mol.m-3]',
 'Average positive particle concentration',
 'Average positive particle concentration [mol.m-3]',
 'Positive particle surface concentration',
 'Positive particle surface concentration [mol.m-3]',
 'X-averaged positive particle surface concentration',
 'X-averaged positive particle surface concentration [mol.m-3]',
 'Positive electrode extent of lithiation',
 'X-averaged positive electrode extent of lithiation',
 'Minimum positive particle concentration',
 'Maximum positive particle concentration',
 'Minimum positive particle concentration [mol.m-3]',
 'Maximum positive particle concentration [mol.m-3]',
 'Minimum positive particle surface concentration',
 'Maximum positive particle surface concentration',
 'Minimum positive particle surface concentration [mol.m-3]',
 'Maximum positive particle surface concentration [mol.m-3]',
```

```
'Porosity times concentration',
'Separator porosity times concentration',
'Positive electrode porosity times concentration',
'Negative electrode porosity times concentration',
'Negative current collector temperature',
'Negative current collector temperature [K]',
'X-averaged negative electrode temperature',
'X-averaged negative electrode temperature [K]',
'Negative electrode temperature',
'Negative electrode temperature [K]',
'X-averaged separator temperature',
'X-averaged separator temperature [K]',
'Separator temperature',
'Separator temperature [K]',
'X-averaged positive electrode temperature',
'X-averaged positive electrode temperature [K]',
'Positive electrode temperature',
'Positive electrode temperature [K]',
'Positive current collector temperature',
'Positive current collector temperature [K]',
'Cell temperature',
'Cell temperature [K]',
'X-averaged cell temperature',
'X-averaged cell temperature [K]',
'Volume-averaged cell temperature',
'Volume-averaged cell temperature [K]',
'Ambient temperature [K]',
'Ambient temperature',
'Negative current collector potential',
'Negative current collector potential [V]',
'Inner SEI thickness',
'Inner SEI thickness [m]',
'Outer SEI thickness',
'Outer SEI thickness [m]',
'X-averaged inner SEI thickness',
'X-averaged inner SEI thickness [m]',
'X-averaged outer SEI thickness',
'X-averaged outer SEI thickness [m]',
'SEI thickness',
'SEI [m]',
'Total SEI thickness',
'Total SEI thickness [m]',
'X-averaged SEI thickness',
'X-averaged SEI thickness [m]',
'X-averaged total SEI thickness',
'X-averaged total SEI thickness [m]',
'X-averaged negative electrode resistance [Ohm.m2]',
```

```
'Inner SEI interfacial current density',
'Inner SEI interfacial current density [A.m-2]',
'X-averaged inner SEI interfacial current density',
'X-averaged inner SEI interfacial current density [A.m-2]',
'Outer SEI interfacial current density',
'Outer SEI interfacial current density [A.m-2]',
'X-averaged outer SEI interfacial current density',
'X-averaged outer SEI interfacial current density [A.m-2]',
'SEI interfacial current density',
'SEI interfacial current density [A.m-2]',
'X-averaged SEI interfacial current density',
'X-averaged SEI interfacial current density [A.m-2]',
'Inner SEI on cracks thickness',
'Inner SEI on cracks thickness [m]',
'Outer SEI on cracks thickness',
'Outer SEI on cracks thickness [m]',
'X-averaged inner SEI on cracks thickness',
'X-averaged inner SEI on cracks thickness [m]',
'X-averaged outer SEI on cracks thickness',
'X-averaged outer SEI on cracks thickness [m]',
'SEI on cracks thickness',
'SEI on cracks [m]',
'Total SEI on cracks thickness',
'Total SEI on cracks thickness [m]',
'X-averaged SEI on cracks thickness',
'X-averaged SEI on cracks thickness [m]',
'X-averaged total SEI on cracks thickness',
'X-averaged total SEI on cracks thickness [m]',
'Inner SEI on cracks interfacial current density',
'Inner SEI on cracks interfacial current density [A.m-2]',
'X-averaged inner SEI on cracks interfacial current density',
'X-averaged inner SEI on cracks interfacial current density [A.m-2]',
'Outer SEI on cracks interfacial current density',
'Outer SEI on cracks interfacial current density [A.m-2]',
'X-averaged outer SEI on cracks interfacial current density',
'X-averaged outer SEI on cracks interfacial current density [A.m-2]',
'SEI on cracks interfacial current density',
'SEI on cracks interfacial current density [A.m-2]',
'X-averaged SEI on cracks interfacial current density',
'X-averaged SEI on cracks interfacial current density [A.m-2]',
'Lithium plating concentration',
'Lithium plating concentration [mol.m-3]',
'X-averaged lithium plating concentration',
'X-averaged lithium plating concentration [mol.m-3]',
'Dead lithium concentration',
'Dead lithium concentration [mol.m-3]',
'X-averaged dead lithium concentration',
```

```
'X-averaged dead lithium concentration [mol.m-3]',
'Lithium plating thickness',
'Lithium plating thickness [m]',
'X-averaged lithium plating thickness [m]',
'Dead lithium thickness',
'Dead lithium thickness [m]',
'X-averaged dead lithium thickness [m]',
'Loss of lithium to lithium plating [mol]',
'Loss of capacity to lithium plating [A.h]',
'Negative electrode lithium plating reaction overpotential',
'X-averaged negative electrode lithium plating reaction overpotential',
'Negative electrode lithium plating reaction overpotential [V]',
'X-averaged negative electrode lithium plating reaction overpotential [V]',
'Lithium plating interfacial current density',
'Lithium plating interfacial current density [A.m-2]',
'X-averaged lithium plating interfacial current density',
'X-averaged lithium plating interfacial current density [A.m-2]',
'Negative crack surface to volume ratio [m-1]',
'Negative crack surface to volume ratio',
'Negative electrode roughness ratio',
'X-averaged negative electrode roughness ratio',
'Positive crack surface to volume ratio [m-1]',
'Positive crack surface to volume ratio',
'Positive electrode roughness ratio',
'X-averaged positive electrode roughness ratio',
'Electrolyte transport efficiency',
'Positive electrolyte transport efficiency',
'X-averaged positive electrolyte transport efficiency',
'Negative electrolyte transport efficiency',
'X-averaged negative electrolyte transport efficiency',
'Separator transport efficiency',
'X-averaged separator transport efficiency',
'Leading-order electrolyte transport efficiency',
'Leading-order positive electrolyte transport efficiency',
'Leading-order x-averaged positive electrolyte transport efficiency',
'Leading-order negative electrolyte transport efficiency',
'Leading-order x-averaged negative electrolyte transport efficiency',
'Leading-order separator transport efficiency',
'Leading-order x-averaged separator transport efficiency',
'Electrode transport efficiency',
'Positive electrode transport efficiency',
'X-averaged positive electrode transport efficiency',
'Negative electrode transport efficiency',
'X-averaged negative electrode transport efficiency',
'Leading-order electrode transport efficiency',
'Leading-order positive electrode transport efficiency',
'Leading-order x-averaged positive electrode transport efficiency',
```

```
'Leading-order negative electrode transport efficiency',
'Leading-order x-averaged negative electrode transport efficiency',
'Separator volume-averaged velocity',
'Separator volume-averaged velocity [m.s-1]',
'Separator volume-averaged acceleration',
'Separator volume-averaged acceleration [m.s-1]',
'X-averaged separator volume-averaged acceleration',
'X-averaged separator volume-averaged acceleration [m.s-1]',
'Volume-averaged velocity',
'Volume-averaged velocity [m.s-1]',
'Volume-averaged acceleration',
'X-averaged volume-averaged acceleration',
'Volume-averaged acceleration [m.s-1]',
'X-averaged volume-averaged acceleration [m.s-1]',
'Pressure',
'Negative electrode open circuit potential',
'Negative electrode open circuit potential [V]',
'X-averaged negative electrode open circuit potential',
'X-averaged negative electrode open circuit potential [V]',
'Negative electrode entropic change',
'Negative electrode entropic change [V.K-1]',
'X-averaged negative electrode entropic change',
'X-averaged negative electrode entropic change [V.K-1]',
'Positive electrode open circuit potential',
'Positive electrode open circuit potential [V]',
'X-averaged positive electrode open circuit potential',
'X-averaged positive electrode open circuit potential [V]',
'Positive electrode entropic change',
'Positive electrode entropic change [V.K-1]',
'X-averaged positive electrode entropic change',
'X-averaged positive electrode entropic change [V.K-1]',
'Negative effective diffusivity',
'Negative effective diffusivity [m2.s-1]',
'X-averaged negative effective diffusivity',
'X-averaged negative effective diffusivity [m2.s-1]',
'Negative particle flux',
'X-averaged negative particle flux',
'Negative electrode SOC',
'Negative electrode volume-averaged concentration',
'Negative electrode volume-averaged concentration [mol.m-3]',
'Total lithium in negative electrode [mol]',
'Positive effective diffusivity',
'Positive effective diffusivity [m2.s-1]',
'X-averaged positive effective diffusivity',
'X-averaged positive effective diffusivity [m2.s-1]',
'Positive particle flux',
'X-averaged positive particle flux',
```

```
'Positive electrode SOC',
'Positive electrode volume-averaged concentration',
'Positive electrode volume-averaged concentration [mol.m-3]',
'Total lithium in positive electrode [mol]',
'Electrolyte concentration',
'Electrolyte concentration [mol.m-3]',
'Electrolyte concentration [Molar]',
'X-averaged electrolyte concentration',
'X-averaged electrolyte concentration [mol.m-3]',
'X-averaged electrolyte concentration [Molar]',
'Negative electrolyte concentration',
'Negative electrolyte concentration [mol.m-3]',
'Negative electrolyte concentration [Molar]',
'Separator electrolyte concentration',
'Separator electrolyte concentration [mol.m-3]',
'Separator electrolyte concentration [Molar]',
'Positive electrolyte concentration',
'Positive electrolyte concentration [mol.m-3]',
'Positive electrolyte concentration [Molar]',
'X-averaged negative electrolyte concentration',
'X-averaged negative electrolyte concentration [mol.m-3]',
'X-averaged separator electrolyte concentration',
'X-averaged separator electrolyte concentration [mol.m-3]',
'X-averaged positive electrolyte concentration',
'X-averaged positive electrolyte concentration [mol.m-3]',
'Ohmic heating',
'Ohmic heating [W.m-3]',
'X-averaged Ohmic heating',
'X-averaged Ohmic heating [W.m-3]',
'Volume-averaged Ohmic heating',
'Volume-averaged Ohmic heating [W.m-3]',
'Irreversible electrochemical heating',
'Irreversible electrochemical heating [W.m-3]',
'X-averaged irreversible electrochemical heating',
'X-averaged irreversible electrochemical heating [W.m-3]',
'Volume-averaged irreversible electrochemical heating',
'Volume-averaged irreversible electrochemical heating[W.m-3]',
'Reversible heating',
'Reversible heating [W.m-3]',
'X-averaged reversible heating',
'X-averaged reversible heating [W.m-3]',
'Volume-averaged reversible heating',
'Volume-averaged reversible heating [W.m-3]',
'Total heating',
'Total heating [W.m-3]',
'X-averaged total heating',
'X-averaged total heating [W.m-3]',
```

```
 'Volume-averaged total heating',
 'Volume-averaged total heating [W.m-3]',
 'Current collector current density',
 'Current collector current density [A.m-2]',
 'Leading-order current collector current density',
 'Inner SEI concentration [mol.m-3]',
 'X-averaged inner SEI concentration [mol.m-3]',
 'Outer SEI concentration [mol.m-3]',
 'X-averaged outer SEI concentration [mol.m-3]',
 'SEI concentration [mol.m-3]',
 'X-averaged SEI concentration [mol.m-3]',
 'Loss of lithium to SEI [mol]',
 'Loss of capacity to SEI [A.h]',
 'X-averaged negative electrode SEI interfacial current density',
 'Negative electrode SEI interfacial current density',
 'Negative electrode SEI interfacial current density [A.m-2]',
 'Negative electrode SEI volumetric interfacial current density',
 'X-averaged negative electrode SEI volumetric interfacial current density',
 'Negative electrode SEI volumetric interfacial current density [A.m-3]',
 'X-averaged negative electrode SEI volumetric interfacial current density
[A.m-3]',
 'X-averaged positive electrode SEI interfacial current density',
 'Positive electrode SEI interfacial current density',
 'Positive electrode SEI interfacial current density [A.m-2]',
 'X-averaged positive electrode SEI volumetric interfacial current density',
 'Positive electrode SEI volumetric interfacial current density',
 'Inner SEI on cracks concentration [mol.m-3]',
 'X-averaged inner SEI on cracks concentration [mol.m-3]',
 'Outer SEI on cracks concentration [mol.m-3]',
 'X-averaged outer SEI on cracks concentration [mol.m-3]',
 'SEI on cracks concentration [mol.m-3]',
 'X-averaged SEI on cracks concentration [mol.m-3]',
 'Loss of lithium to SEI on cracks [mol]',
 'Loss of capacity to SEI on cracks [A.h]',
 'X-averaged negative electrode SEI on cracks interfacial current density',
 'Negative electrode SEI on cracks interfacial current density',
 'Negative electrode SEI on cracks interfacial current density [A.m-2]',
 'Negative electrode SEI on cracks volumetric interfacial current density',
 'X-averaged negative electrode SEI on cracks volumetric interfacial current
density',
 'Negative electrode SEI on cracks volumetric interfacial current density
[A.m-3]',
 'X-averaged negative electrode SEI on cracks volumetric interfacial current
density [A.m-3]',
 'X-averaged positive electrode SEI on cracks interfacial current density',
 'Positive electrode SEI on cracks interfacial current density',
 'Positive electrode SEI on cracks interfacial current density [A.m-2]',
```

```
 'X-averaged positive electrode SEI on cracks volumetric interfacial current
density',
 'Positive electrode SEI on cracks volumetric interfacial current density',
 'X-averaged negative electrode lithium plating interfacial current density',
 'X-averaged positive electrode lithium plating interfacial current density',
 'X-averaged positive electrode lithium plating volumetric interfacial current
density',
 'Negative electrode lithium plating interfacial current density',
 'Negative electrode lithium plating interfacial current density [A.m-2]',
 'Positive electrode lithium plating interfacial current density',
 'Positive electrode lithium plating interfacial current density [A.m-2]',
 'Positive electrode lithium plating volumetric interfacial current density',
 'Negative electrode lithium plating volumetric interfacial current density',
 'X-averaged negative electrode lithium plating volumetric interfacial current
density',
 'Negative electrode lithium plating volumetric interfacial current density
[A.m-3]',
 'X-averaged negative electrode lithium plating volumetric interfacial current
density [A.m-3]',
 'X-averaged negative electrode total interfacial current density',
 'X-averaged negative electrode total interfacial current density [A.m-2]',
 'SEI film overpotential',
 'X-averaged SEI film overpotential',
 'SEI film overpotential [V]',
 'X-averaged SEI film overpotential [V]',
 'Negative electrode exchange current density',
 'X-averaged negative electrode exchange current density',
 'Negative electrode exchange current density [A.m-2]',
 'X-averaged negative electrode exchange current density [A.m-2]',
 'Negative electrode reaction overpotential',
 'X-averaged negative electrode reaction overpotential',
 'Negative electrode reaction overpotential [V]',
 'X-averaged negative electrode reaction overpotential [V]',
 'X-averaged negative electrode surface potential difference',
 'X-averaged negative electrode surface potential difference [V]',
 'X-averaged positive electrode total interfacial current density',
 'X-averaged positive electrode total interfacial current density [A.m-2]',
 'Positive electrode exchange current density',
 'X-averaged positive electrode exchange current density',
 'Positive electrode exchange current density [A.m-2]',
 'X-averaged positive electrode exchange current density [A.m-2]',
 'Positive electrode reaction overpotential',
 'X-averaged positive electrode reaction overpotential',
 'Positive electrode reaction overpotential [V]',
 'X-averaged positive electrode reaction overpotential [V]',
 'X-averaged positive electrode surface potential difference',
 'X-averaged positive electrode surface potential difference [V]',
```

```
'Negative electrode interfacial current density',
'X-averaged negative electrode interfacial current density',
'Negative electrode interfacial current density [A.m-2]',
'X-averaged negative electrode interfacial current density [A.m-2]',
'Negative electrode volumetric interfacial current density',
'X-averaged negative electrode volumetric interfacial current density',
'Negative electrode volumetric interfacial current density [A.m-3]',
'X-averaged negative electrode volumetric interfacial current density [A.m-3]',
'Positive electrode interfacial current density',
'X-averaged positive electrode interfacial current density',
'Positive electrode interfacial current density [A.m-2]',
'X-averaged positive electrode interfacial current density [A.m-2]',
'Positive electrode volumetric interfacial current density',
'X-averaged positive electrode volumetric interfacial current density',
'Positive electrode volumetric interfacial current density [A.m-3]',
'X-averaged positive electrode volumetric interfacial current density [A.m-3]',
'Negative electrode potential',
'Negative electrode potential [V]',
'X-averaged negative electrode potential',
'X-averaged negative electrode potential [V]',
'Negative electrode ohmic losses',
'Negative electrode ohmic losses [V]',
'X-averaged negative electrode ohmic losses',
'X-averaged negative electrode ohmic losses [V]',
'Gradient of negative electrode potential',
'Negative electrode current density',
'Negative electrode current density [A.m-2]',
'Negative electrolyte potential',
'Negative electrolyte potential [V]',
'Separator electrolyte potential',
'Separator electrolyte potential [V]',
'Positive electrolyte potential',
'Positive electrolyte potential [V]',
'Electrolyte potential',
'Electrolyte potential [V]',
'X-averaged electrolyte potential',
'X-averaged electrolyte potential [V]',
'X-averaged negative electrolyte potential',
'X-averaged negative electrolyte potential [V]',
'X-averaged separator electrolyte potential',
'X-averaged separator electrolyte potential [V]',
'X-averaged positive electrolyte potential',
'X-averaged positive electrolyte potential [V]',
'X-averaged electrolyte overpotential',
'X-averaged electrolyte overpotential [V]',
'Gradient of separator electrolyte potential',
'Gradient of positive electrolyte potential',
```

```
 'Gradient of electrolyte potential',
 'Gradient of negative electrolyte potential',
 'Electrolyte current density',
 'Electrolyte current density [A.m-2]',
 'Negative electrolyte current density',
 'Negative electrolyte current density [A.m-2]',
 'Positive electrolyte current density',
 'Positive electrolyte current density [A.m-2]',
 'X-averaged concentration overpotential',
 'X-averaged electrolyte ohmic losses',
 'X-averaged concentration overpotential [V]',
 'X-averaged electrolyte ohmic losses [V]',
 'Negative electrode surface potential difference',
 'Negative electrode surface potential difference [V]',
 'Electrolyte flux',
 'Electrolyte flux [mol.m-2.s-1]',
 'Total lithium in electrolyte',
 'Total lithium in electrolyte [mol]',
 'Sum of electrolyte reaction source terms',
 'Sum of positive electrode electrolyte reaction source terms',
 'Sum of x-averaged positive electrode electrolyte reaction source terms',
 'Sum of interfacial current densities',
 'Sum of volumetric interfacial current densities',
 'Sum of positive electrode interfacial current densities',
 'Sum of x-averaged positive electrode interfacial current densities',
 'Sum of positive electrode volumetric interfacial current densities',
 'Sum of x-averaged positive electrode volumetric interfacial current
densities',
 'Sum of negative electrode electrolyte reaction source terms',
 'Sum of x-averaged negative electrode electrolyte reaction source terms',
 'Sum of negative electrode interfacial current densities',
 'Sum of x-averaged negative electrode interfacial current densities',
 'Sum of negative electrode volumetric interfacial current densities',
 'Sum of x-averaged negative electrode volumetric interfacial current
densities',
 'Interfacial current density',
 'Interfacial current density [A.m-2]',
 'Exchange current density',
 'Exchange current density [A.m-2]',
 'Positive electrode potential',
 'Positive electrode potential [V]',
 'X-averaged positive electrode potential',
 'X-averaged positive electrode potential [V]',
 'Positive electrode ohmic losses',
 'Positive electrode ohmic losses [V]',
 'X-averaged positive electrode ohmic losses',
 'X-averaged positive electrode ohmic losses [V]',
```

```
'Gradient of positive electrode potential',
'Positive electrode current density',
'Positive electrode current density [A.m-2]',
'Electrode current density',
'Positive current collector potential',
'Positive current collector potential [V]',
'Local voltage',
'Local voltage [V]',
'Terminal voltage',
'Terminal voltage [V]',
'Positive electrode surface potential difference',
'Positive electrode surface potential difference [V]',
'X-averaged open circuit voltage',
'Measured open circuit voltage',
'X-averaged open circuit voltage [V]',
'Measured open circuit voltage [V]',
'X-averaged reaction overpotential',
'X-averaged reaction overpotential [V]',
'X-averaged solid phase ohmic losses',
'X-averaged solid phase ohmic losses [V]',
'X-averaged battery open circuit voltage [V]',
'Measured battery open circuit voltage [V]',
'X-averaged battery reaction overpotential [V]',
'X-averaged battery solid phase ohmic losses [V]',
'X-averaged battery electrolyte ohmic losses [V]',
'X-averaged battery concentration overpotential [V]',
'Battery voltage [V]',
'Change in measured open circuit voltage',
'Change in measured open circuit voltage [V]',
'Local ECM resistance',
'Local ECM resistance [Ohm]',
'Terminal power [W]',
'Power [W]',
'Resistance [Ohm]',
'LAM_ne [%]',
'LAM_pe [%]',
'LLI [%]',
'Loss of active material in negative electrode [%]',
'Loss of active material in positive electrode [%]',
'Loss of lithium inventory [%]',
'Loss of lithium inventory, including electrolyte [%]',
'Total lithium [mol]',
'Total lithium in particles [mol]',
'Total lithium lost [mol]',
'Total lithium lost from particles [mol]',
'Total lithium lost from electrolyte [mol]',
'Total lithium lost to side reactions [mol]',
```

```
 'Total capacity lost to side reactions [A.h]']
```

[45]:
```
print(netlist)          #Extra Step
```

```
      desc  node1  node2     value  node1_x  node1_y  node2_x  node2_y  \
0     Rbn0      1      2  0.000001        0        0        1        0
1     Rbn1      2      3  0.000001        1        0        2        0
2     Rbn2      3      4  0.000001        2        0        3        0
3     Rbn3      4      5  0.000001        3        0        4        0
4     Rbn4      5      6  0.000001        4        0        5        0
..     …    …    …       …       …       …       …
249  Rbp18    240    241  0.000001        8       21        9       21
250  Rbp19    241    242  0.000001        9       21       10       21
251   Rtp1    232    243  0.000010        0       21       -1       21
252     I0    243      0  0.000000       -1       21       -1        0
253   Rtn1      0      1  0.000010       -1        0        0        0

       power_loss
0    5.043662e-17
1    3.845905e-18
2    4.100815e-18
3    3.834557e-17
4    5.090466e-17
..            …
249  3.426067e-18
250  1.490139e-16
251  1.262177e-24
252  0.000000e+00
253  1.727921e-21

[254 rows x 9 columns]
```

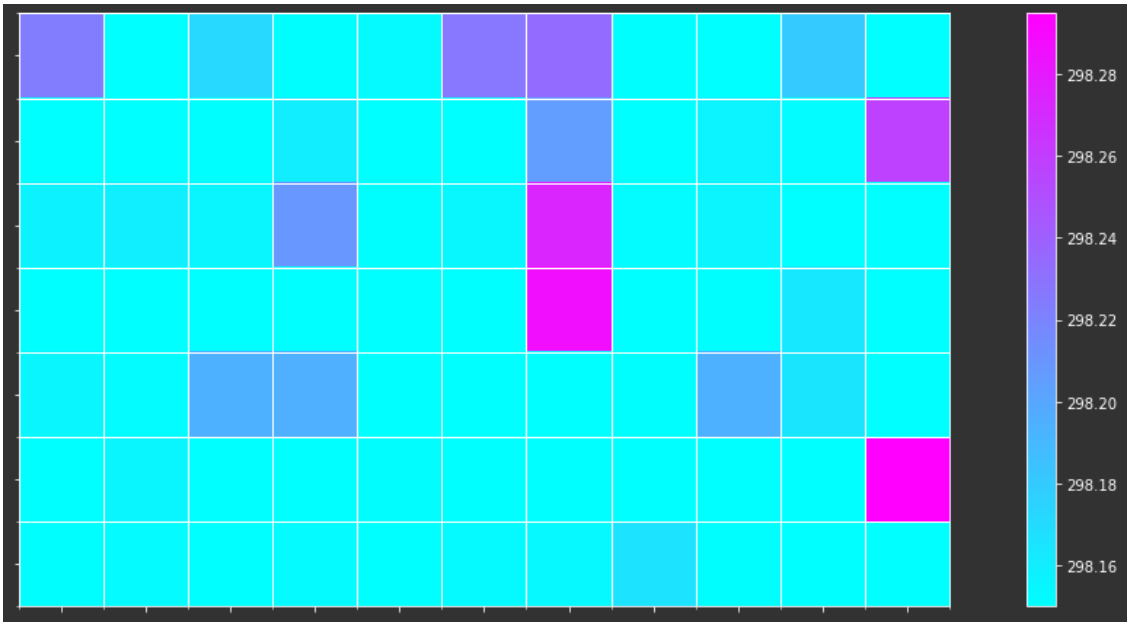
[54]:
```
output
```

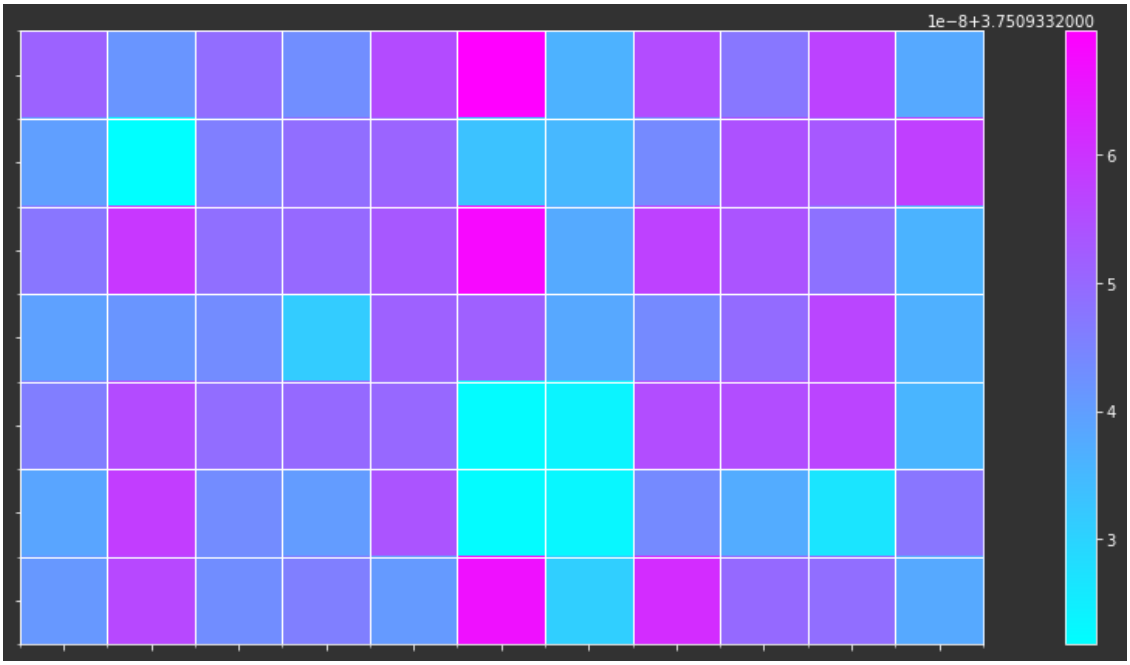
[54]:
```
{'Time [s]': array([0.000e+00, 1.000e+01, 2.000e+01, …, 1.618e+04, 1.619e+04,
        1.620e+04]),
 'Pack current [A]': array([2., 2., 2., …, 0., 0., 0.]),
 'Pack terminal voltage [V]': array([26.2157441 , 26.20835345, 26.20353291, …,
26.25659955,
        26.25656564, 26.25653272]),
 'Cell current [A]': array([[1.81878780e-01, 1.81878781e-01, 1.81878781e-01,
…,
         1.81783556e-01, 1.81783556e-01, 1.81783556e-01],
        [1.81875691e-01, 1.81875694e-01, 1.81875693e-01, …,
         1.81785319e-01, 1.81785319e-01, 1.81785319e-01],
        [1.81865788e-01, 1.81865787e-01, 1.81865787e-01, …,
         1.81790978e-01, 1.81790978e-01, 1.81790978e-01],
        …,
```

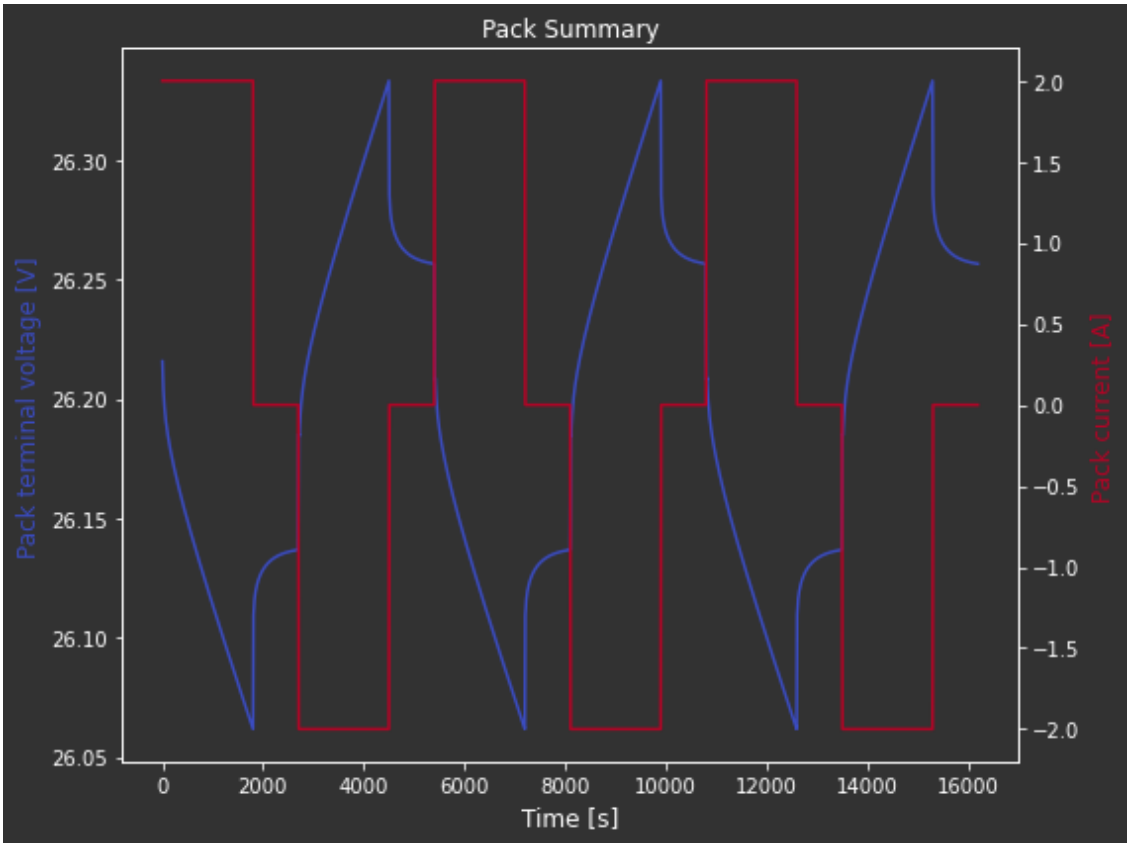
```
        [7.26449660e-06, 7.26512571e-06, 7.26676508e-06, …,
         1.25353094e-05, 1.25353094e-05, 1.25353094e-05],
        [7.20277266e-06, 7.20392802e-06, 7.20460842e-06, …,
         1.24243105e-05, 1.24243105e-05, 1.24243105e-05],
        [7.14204378e-06, 7.14163083e-06, 7.14356185e-06, …,
         1.23144078e-05, 1.23144078e-05, 1.23144078e-05]]),
 'Cell internal resistance [Ohm]': array([[0.03166047, 0.03166047, 0.03166047,
…, 0.0316605 , 0.0316605 ,
         0.0316605 ],
        [0.03344702, 0.03344703, 0.03344702, …, 0.03344708, 0.03344707,
         0.03344708],
        [0.03467282, 0.03467285, 0.03467283, …, 0.03467267, 0.03467264,
         0.03467266],
        …,
        [0.03808004, 0.03816887, 0.03815205, …, 0.03816954, 0.03800977,
         0.03816664],
        [0.03808004, 0.03816887, 0.03815205, …, 0.03816954, 0.03800977,
         0.03816664],
        [0.03808004, 0.03816887, 0.03815205, …, 0.03816954, 0.03800977,
         0.03816664]]),
 'Terminal voltage [V]': array([[3.7451121 , 3.7451121 , 3.7451121 , …,
3.74511511, 3.74511511,
         3.74511511],
        [3.74405606, 3.74405606, 3.74405606, …, 3.74405943, 3.74405944,
         3.74405943],
        [3.74336743, 3.74336742, 3.74336742, …, 3.74337056, 3.74337056,
         3.74337056],
        …,
        [3.7509428 , 3.75094279, 3.75094279, …, 3.75094278, 3.75094279,
         3.75094278],
        [3.75093795, 3.75093794, 3.75093795, …, 3.75093794, 3.75093795,
         3.75093794],
        [3.75093325, 3.75093324, 3.75093325, …, 3.75093324, 3.75093325,
         3.75093324]]),
 'Measured battery open circuit voltage [V]': array([[3.75087047, 3.75087047,
3.75087047, …, 3.75087047, 3.75087047,
         3.75087047],
        [3.75013926, 3.75013926, 3.75013926, …, 3.75013962, 3.75013962,
         3.75013962],
        [3.74967323, 3.74967323, 3.74967323, …, 3.74967374, 3.74967374,
         3.74967374],
        …,
        [3.75094307, 3.75094306, 3.75094307, …, 3.75094326, 3.75094327,
         3.75094326],
        [3.75093823, 3.75093822, 3.75093823, …, 3.75093841, 3.75093842,
         3.75093841],
        [3.75093352, 3.75093351, 3.75093352, …, 3.75093371, 3.75093372,
```

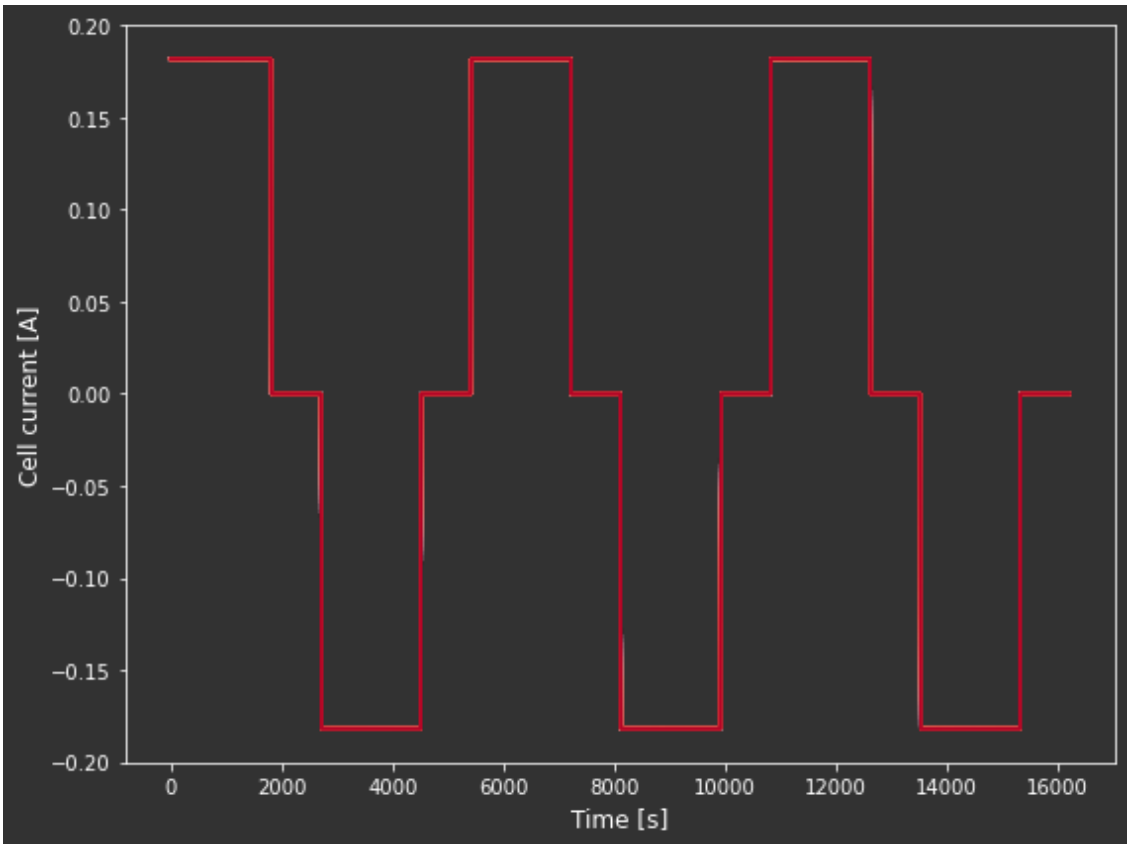
```
        3.75093371]]),
 'Volume-averaged cell temperature [K]': array([[298.15      , 298.15      ,
298.15      , …, 298.15      ,
        298.15      , 298.15      ],
       [298.15029562, 298.15028925, 298.15029402, …, 298.15028832,
        298.15029553, 298.15029048],
       [298.15060373, 298.15057822, 298.15059725, …, 298.15057516,
        298.15060401, 298.15058371],
       …,
       [298.22433434, 298.1501309 , 298.15726363, …, 298.15008125,
        298.29508945, 298.15042136],
       [298.22413496, 298.15012498, 298.15716547, …, 298.15007724,
        298.29489951, 298.15040653],
       [298.22393612, 298.15011932, 298.15706863, …, 298.15007342,
        298.29470981, 298.15039222]])}
```

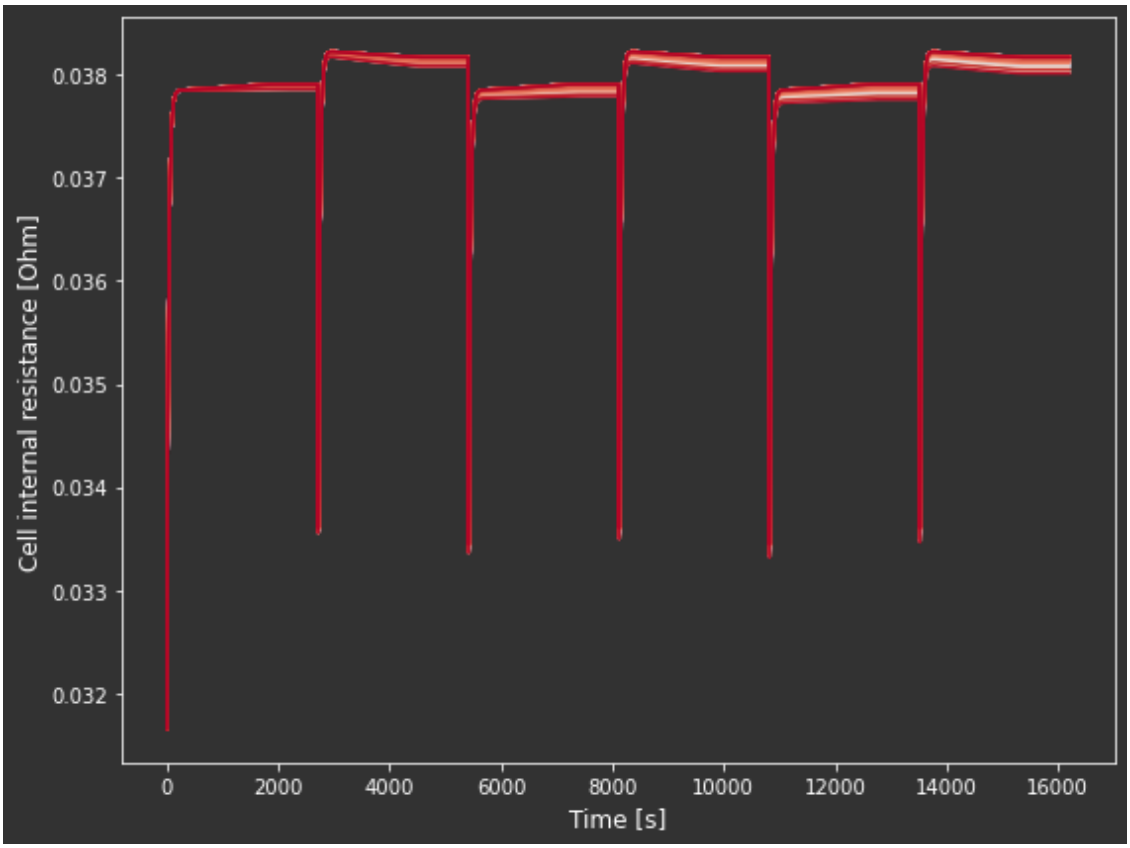
[44]:
```
#use plot_cell_data_image to produce a snapshot of the system in image format␣
 ↪which has the same dimensions as the number of
#cells in parallel and series.
data = output["Volume-averaged cell temperature [K]"][-1, :]
lp.plot_cell_data_image(netlist, data, tick_labels=False, figsize=(15, 6))

data = output["Terminal voltage [V]"][-1, :]
lp.plot_cell_data_image(netlist, data, tick_labels=False, figsize=(15, 6))

lp.plot_output(output)
```

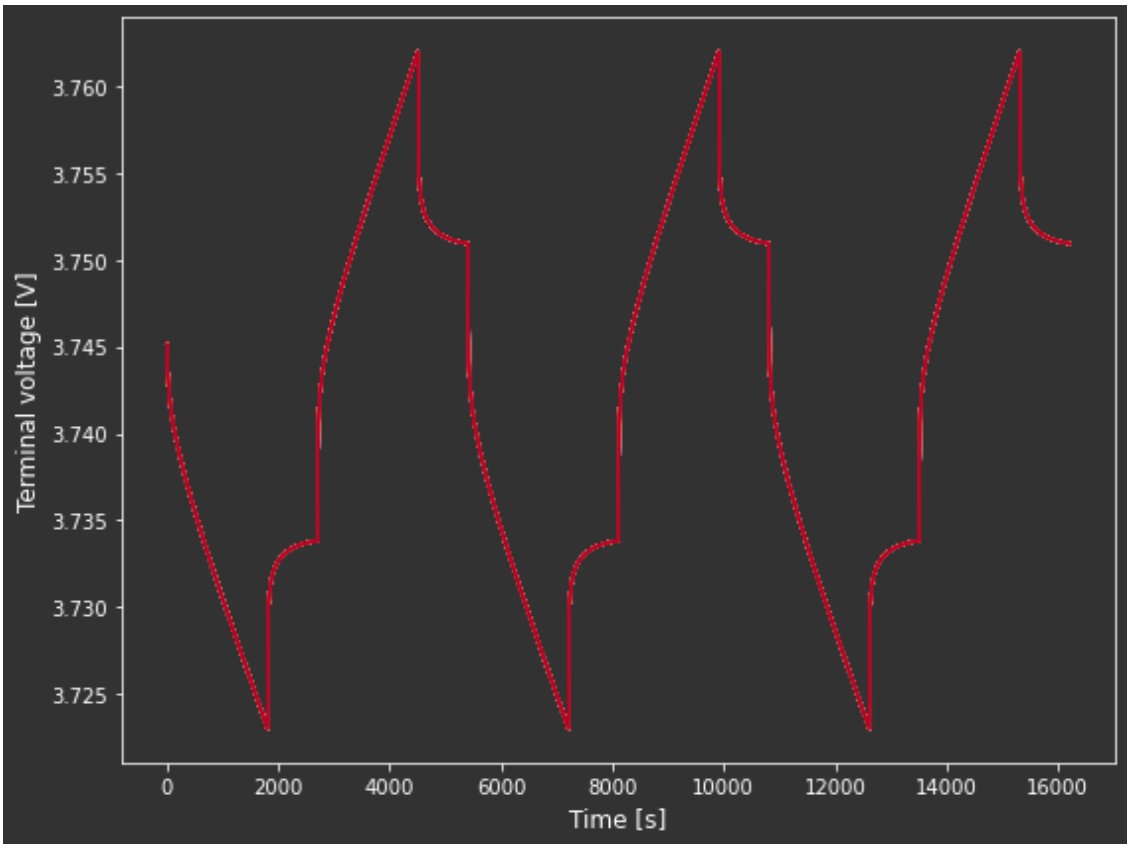


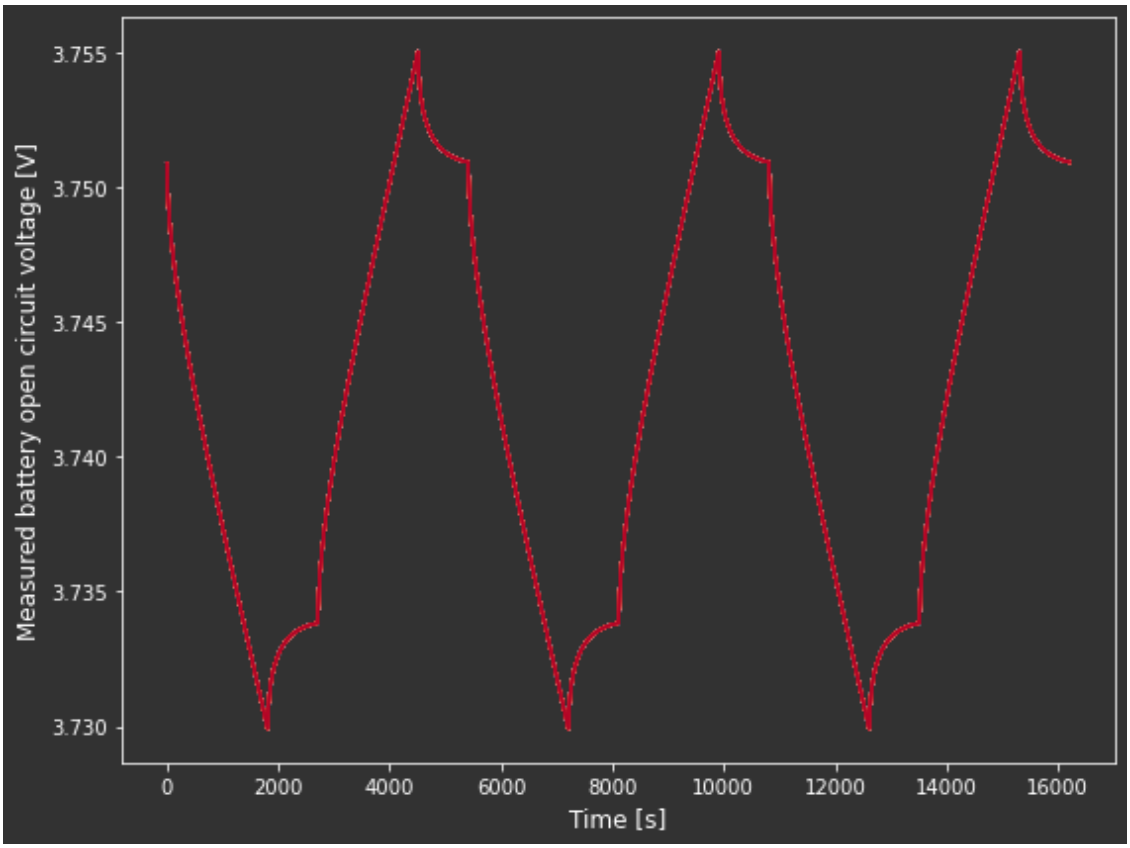

1e−8+3.7509332000
6
5
4
3

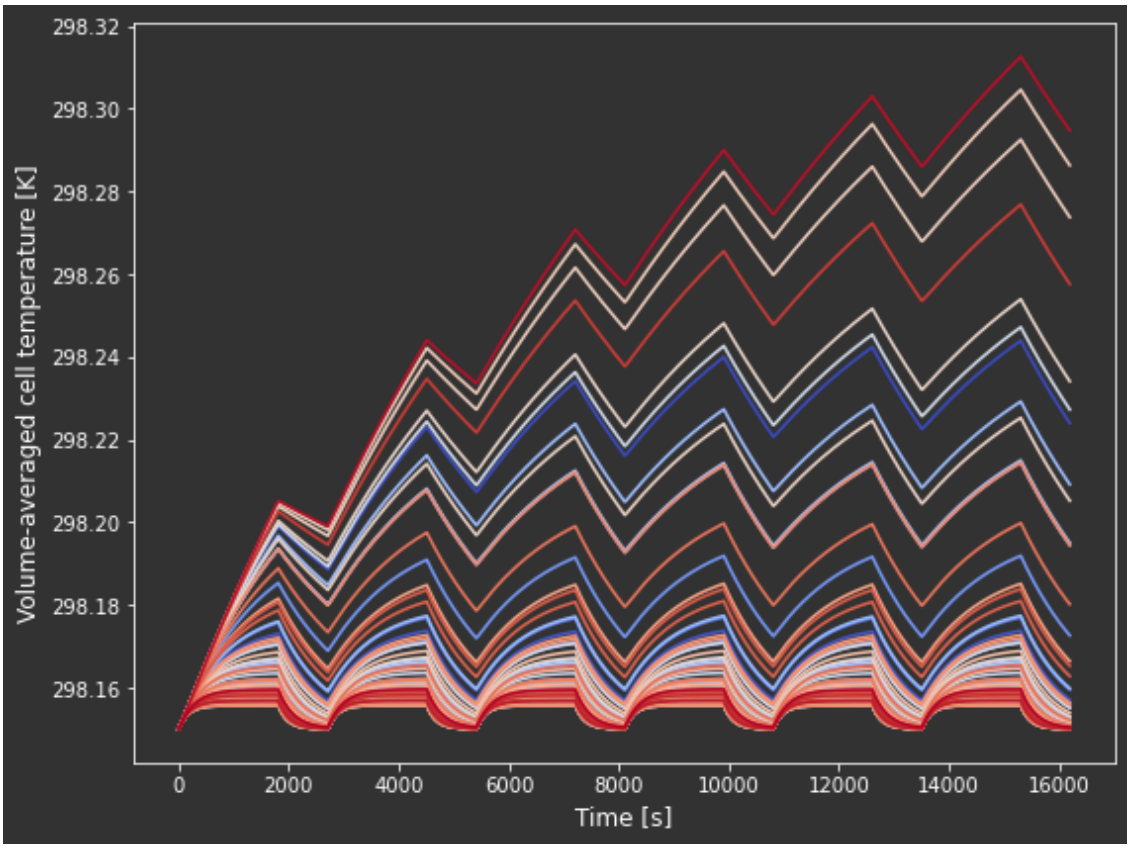

Pack Summary
Pack terminal voltage [V]
Pack current [A]
Time [s]
26.30
26.25
26.20
26.15
26.10
26.05
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
0
2000
4000
6000
8000
10000
12000
14000
16000


0.20
0.15
0.10
0.05
0.00
−0.05
−0.10
−0.15
−0.20
Cell current [A]
0
2000
4000
6000
8000
10000
12000
14000
16000
Time [s]


Cell internal resistance [Ohm]
0.038
0.037
0.036
0.035
0.034
0.033
0.032
0
2000
4000
6000
8000
10000
12000
14000
16000
Time [s]


3.760
3.755
3.750
3.745
3.740
3.735
3.730
3.725
Terminal voltage [V]
0
2000
4000
6000
8000
10000
12000
14000
16000
Time [s]


3.755
3.750
3.745
3.740
3.735
3.730
Measured battery open circuit voltage [V]
0
2000
4000
6000
8000
10000
12000
14000
16000
Time [s]



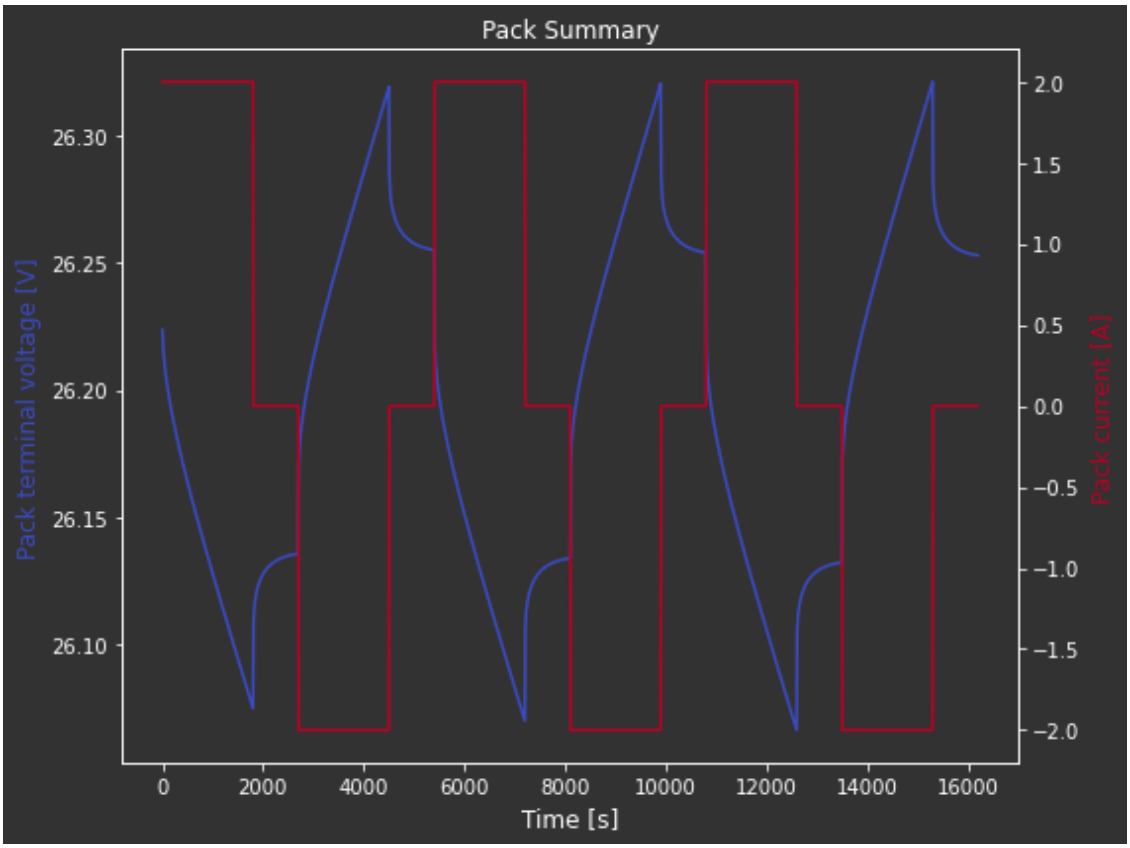
[1]:
```
#defiine SEI degradation : Aging Mechanism Overview of Simulation process and␣
 ↪Steps
def SEI_degradation(parameter_values=None):
    """
    Create a PyBaMM simulation set up for integration with liionpack

    Args:
        parameter_values (pybamm.ParameterValues):
            The default is None.

    Returns:
        pybamm.Simulation:
            A simulation that can be solved individually or passed into the
            liionpack solve method

    """
    # Create the pybamm model
    model = pybamm.lithium_ion.SPM(
        options={
            "SEI": "ec reaction limited",
```

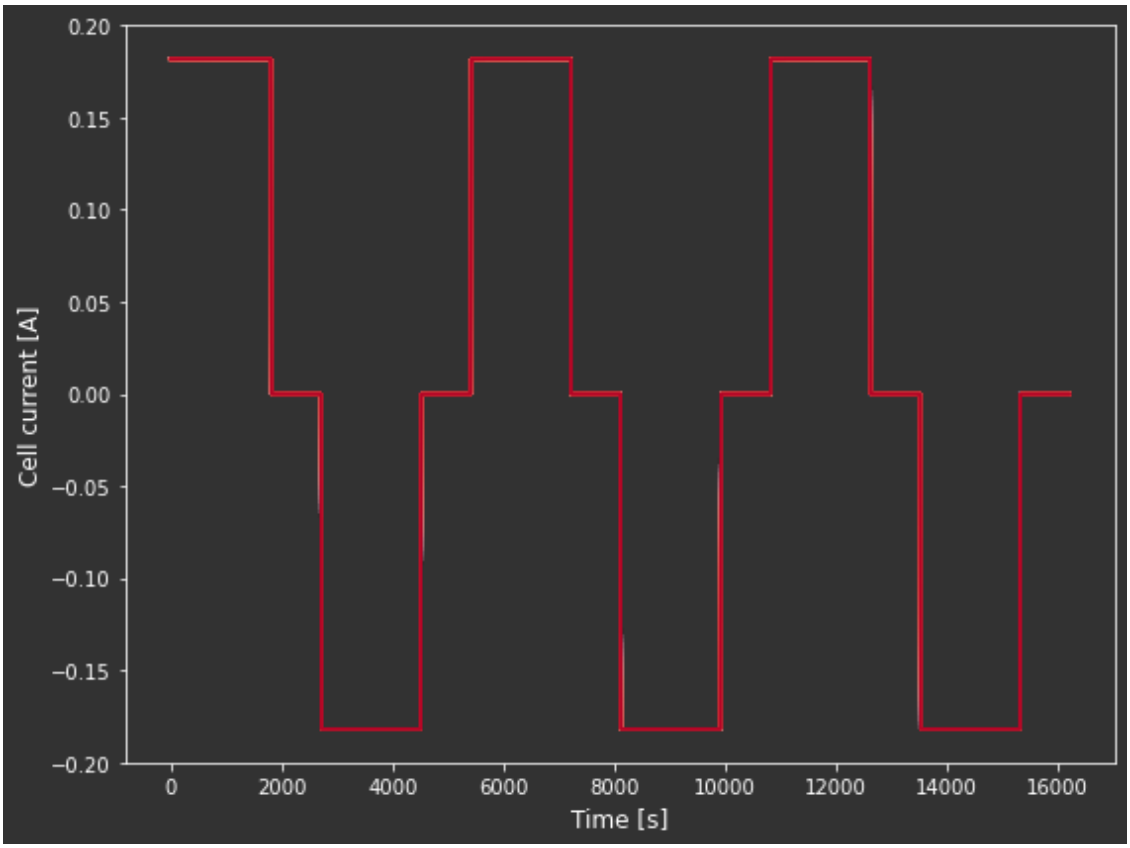
```
            "SEI film resistance": "distributed",
            "SEI porosity change": "true",
        }
    )

    # Add events to the model
    model = lp.add_events_to_model(model)

    # Set up parameter values
    if parameter_values is None:
        parameter_values = pybamm.ParameterValues("Chen2020")

    # Set up solver and simulation
    solver = pybamm.CasadiSolver(mode="safe")
    sim = pybamm.Simulation(
        model=model,
        parameter_values=parameter_values,
        solver=solver,
    )

    return sim
```

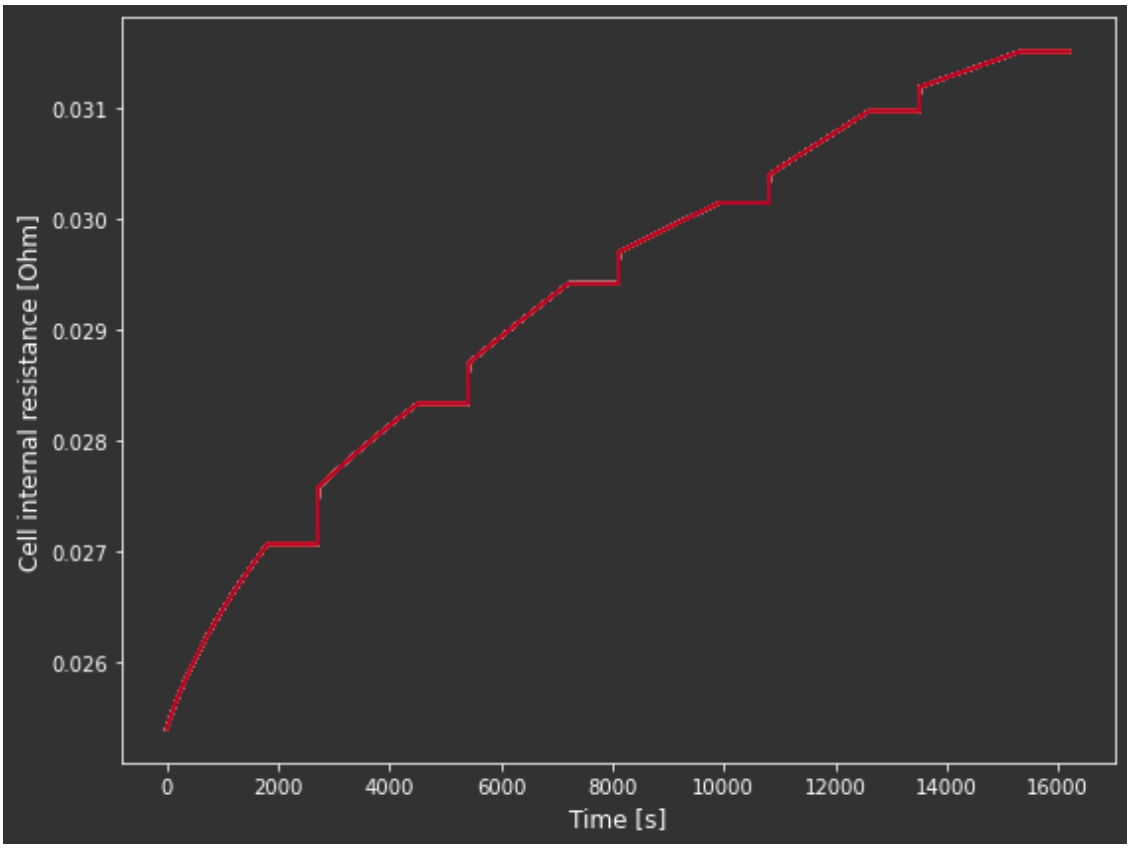
[79]:
```
#SEI Degradation Model:This notebook demonstrates the ageing of cells in a␣
 ↪battery pack.
try:
    import liionpack as lp
except:
    !pip install -q git+https://github.com/pybamm-team/liionpack.git@main
    import liionpack as lp
import pybamm
import numpy as np
Np = 11
Ns = 7
I_mag = 2.0
Rsmall = 1e-6
OCV_init = 4.0
Nspm = Np * Ns
# Generate the netlist
netlist = lp.setup_circuit(Np=Np, Ns=Ns, Rb=Rsmall, Rc=Rsmall, Ri=3e-2,␣
 ↪I=I_mag, V=OCV_init)
# Define additional output variables
output_variables = [
    "Volume-averaged cell temperature [K]",
]
# Define a cycling experiment using PyBaMM
experiment = pybamm.Experiment(                                          ␣
 ↪#experiment for constant charge
```

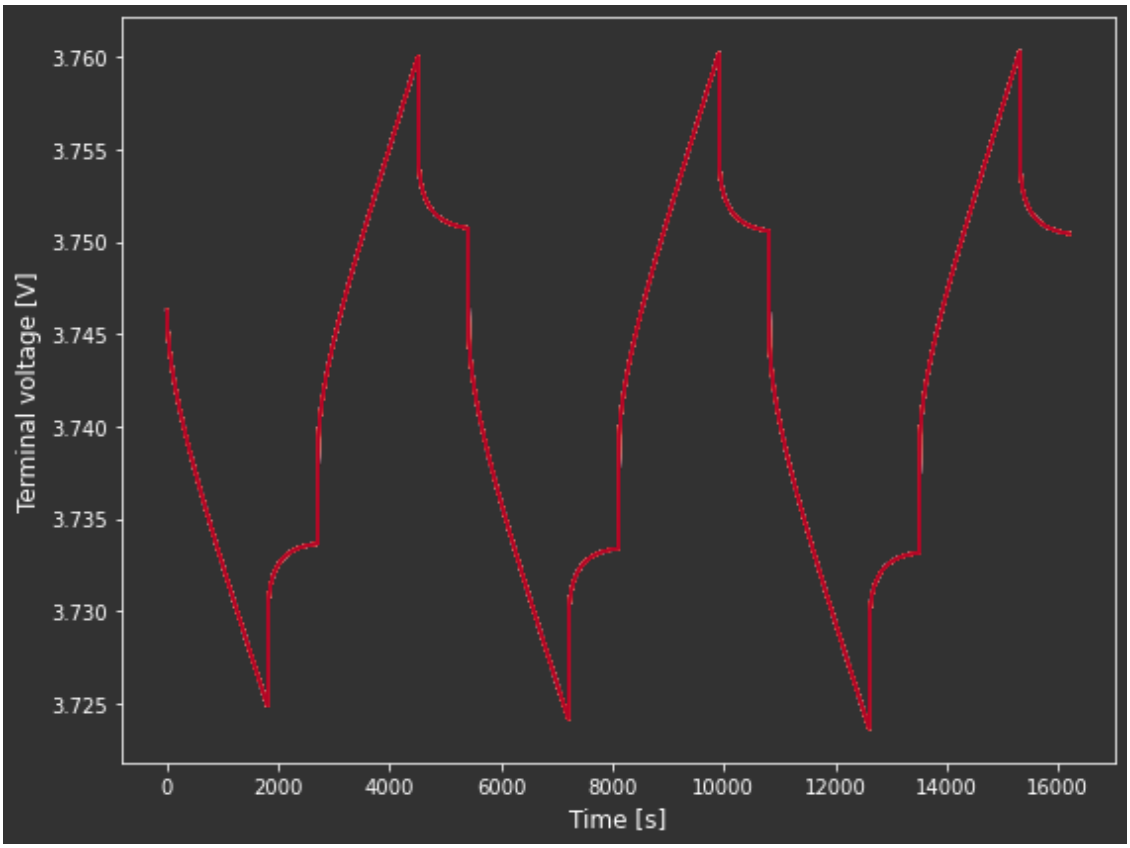
```
    [
        "Charge at 2 A for 30 minutes",
        "Rest for 15 minutes",
        "Discharge at 2 A for 30 minutes",
        "Rest for 15 minutes",
     ]
    * 3,
    period="10 seconds",
)
experiment = pybamm.Experiment(                                                 ␣
 ↪#experiment for constant discharge
    [
        (
        "Discharge at 2 A for 30 minutes",
        "Rest for 15 minutes",
        "Charge at 2 A for 30 minutes",
        "Rest for 15 minutes",
        )
    ]
    * 3,
    period="10 seconds",
)
output_variables = [                    #Let's pick a variables for the output
    'X-averaged total SEI thickness [m]',
    'Loss of capacity to SEI [A.h]',
    ]
output = lp.solve(          #Output and view
    netlist=netlist,
    parameter_values=parameter_values,
    experiment=experiment,
    sim_func=SEI_degradation,
    output_variables=output_variables,
    initial_soc=0.5,
)
lp.plot_output(output)
```

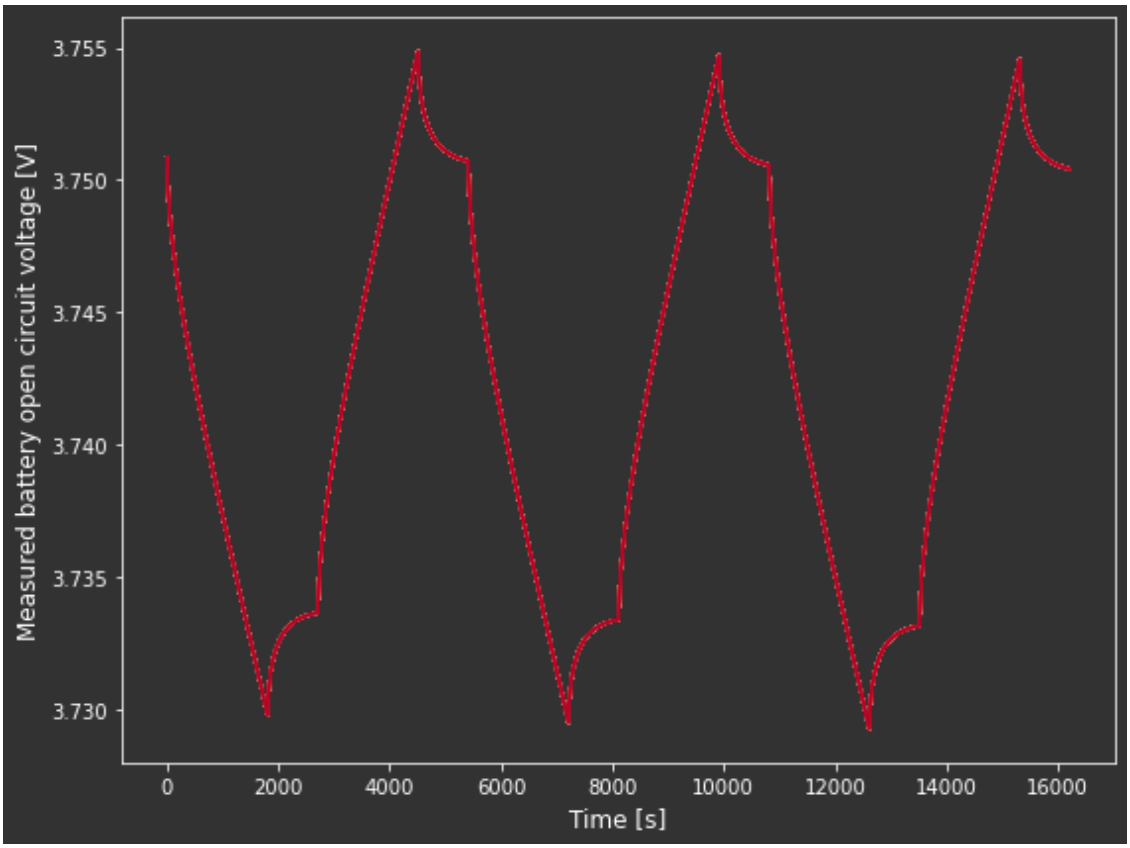
```
Stepping simulation: 100%|      | 1621/1621 [01:03<00:00, 25.64it/s]
```

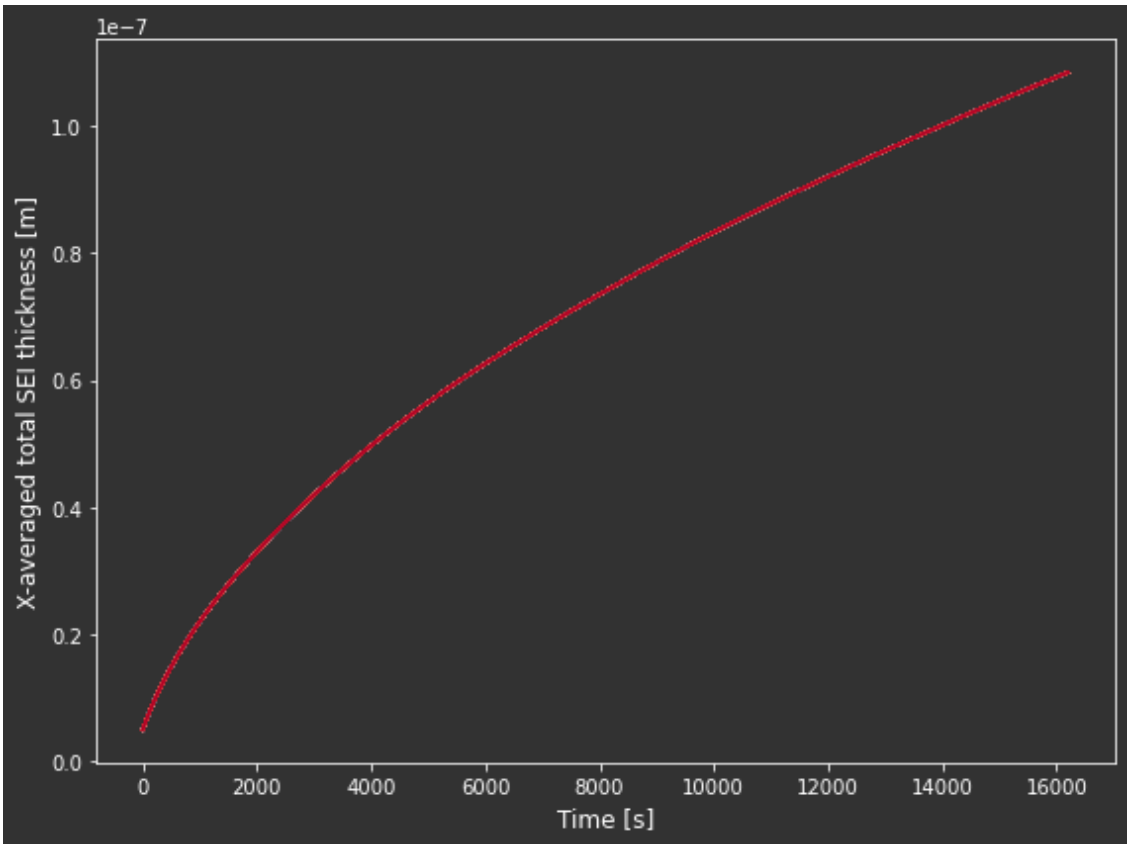

Pack Summary
Pack terminal voltage [V]
Pack current [A]
Time [s]
26.30
26.25
26.20
26.15
26.10
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
0
2000
4000
6000
8000
10000
12000
14000
16000

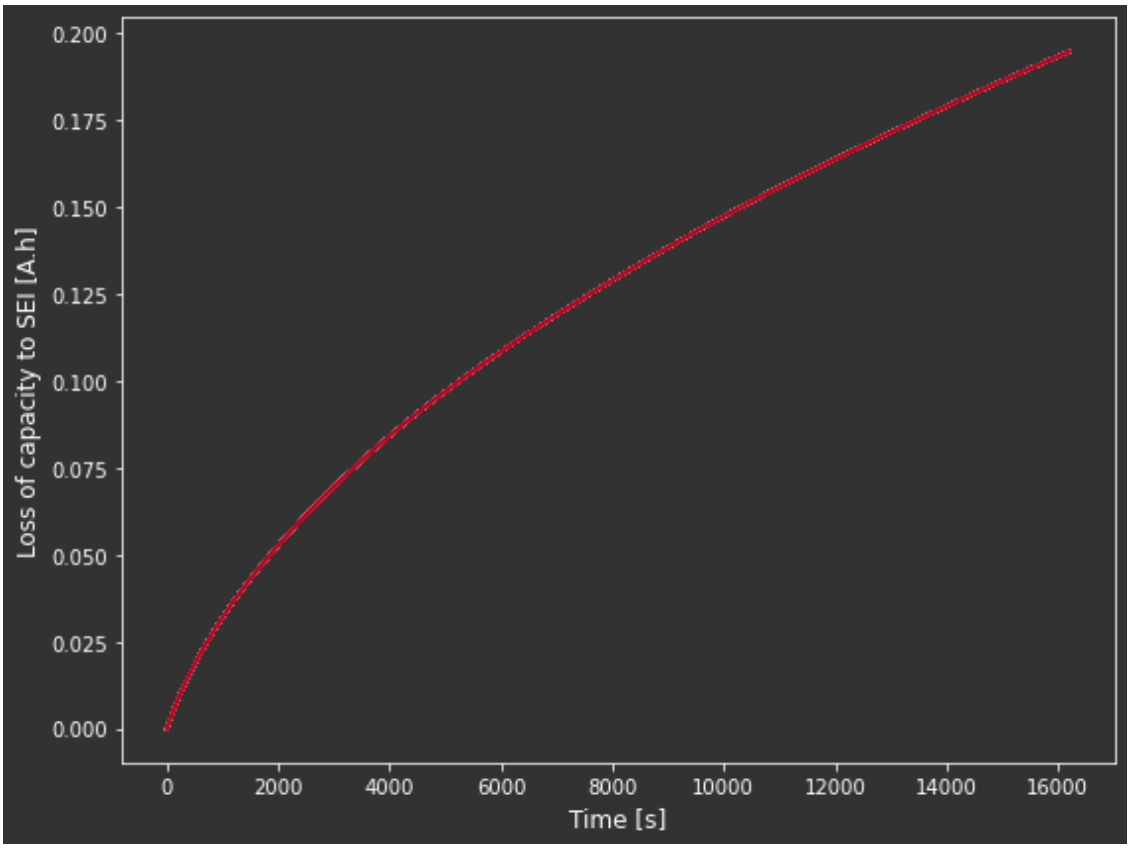

0.20
0.15
0.10
0.05
0.00
−0.05
−0.10
−0.15
−0.20
Cell current [A]
0
2000
4000
6000
8000
10000
12000
14000
16000
Time [s]


Cell internal resistance [Ohm]
0.031
0.030
0.029
0.028
0.027
0.026
0
2000
4000
6000
8000
10000
12000
14000
16000
Time [s]


3.760
3.755
3.750
3.745
3.740
3.735
3.730
3.725
Terminal voltage [V]
0
2000
4000
6000
8000
10000
12000
14000
16000
Time [s]


3.755
3.750
3.745
3.740
3.735
3.730
Measured battery open circuit voltage [V]
0
2000
4000
6000
8000
10000
12000
14000
16000
Time [s]


1e−7
1.0
0.8
0.6
0.4
0.2
0.0
X-averaged total SEI thickness [m]
0
2000
4000
6000
8000
10000
12000
14000
16000
Time [s]


0.200
0.175
0.150
0.125
0.100
0.075
0.050
0.025
0.000
Loss of capacity to SEI [A.h]
0
2000
4000
6000
8000
10000
12000
14000
16000
Time [s]

[ ]:

[ ]:

[ ]: