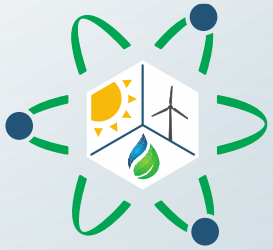

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Integrated Energy Systems

HERON Wind/NPP Case

FORCE Overview and Training

April 4-6, 2023

Gabriel J. Soto Gonzalez, Paul Talbot

Modeling and Simulation Engineer

Idaho National Laboratory

Idaho National Laboratory

Outline

- Wind and Nuclear Power Plant (NPP) Case
  - Basic schematic of Integrated Energy Systems (IES) components
  - Market and Weather scenarios
  - Holistic Energy Resource Optimization Network (HERON) Workflow
  - HERON Input script
  - Running HERON simulation in Debug Mode
  - Running HERON simulation in Sweep Mode
- Adding Arbitrage

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NPP and Wind

Stronger Together (Sometimes)

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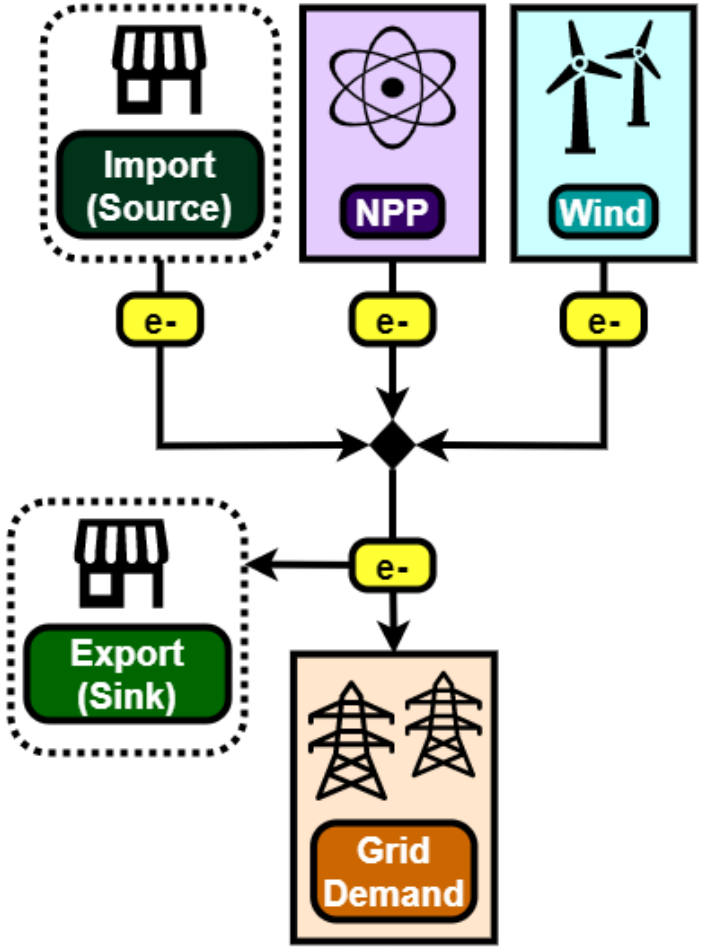
Basic Schematic of IES

- **Nuclear Power Plant**
  - Can flex from 0%–100% of rated capacity
- **Wind Farm**
  - Also has rated capacity, but varies based on wind speeds
    - Capacity factor taken from synthetic histories
- **Electricity Grid**
  - Demand
    - also taken from synthetic histories
  - External Market (Source/Sink)



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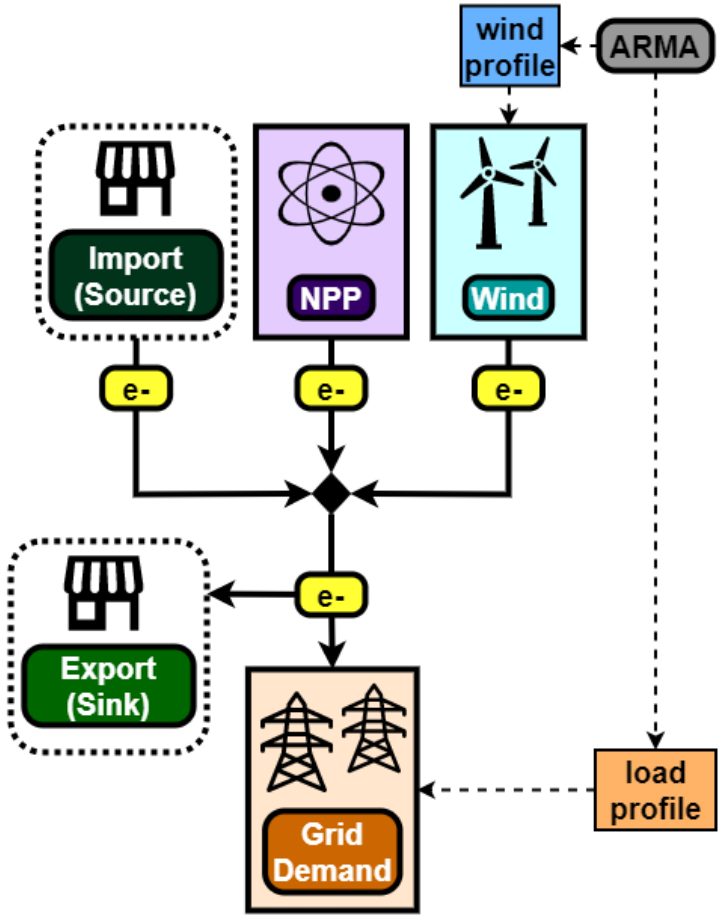
Basic Schematic of IES

- **Given:**
  - IES (NPP + Wind Farm)
  - Market and Geographic Region
- **Need to find:**
  - Capacities
  - Dispatch strategies
- **Goal(s):**
  - Satisfy demand
  - Minimize costs/maximize profits (net present value [NPV])
- **Recall:**
  - Load profiles and weather contain uncertainty
  - Uncertainty represented using synthetic time histories (Auto-Regressive Moving Average [ARMA])



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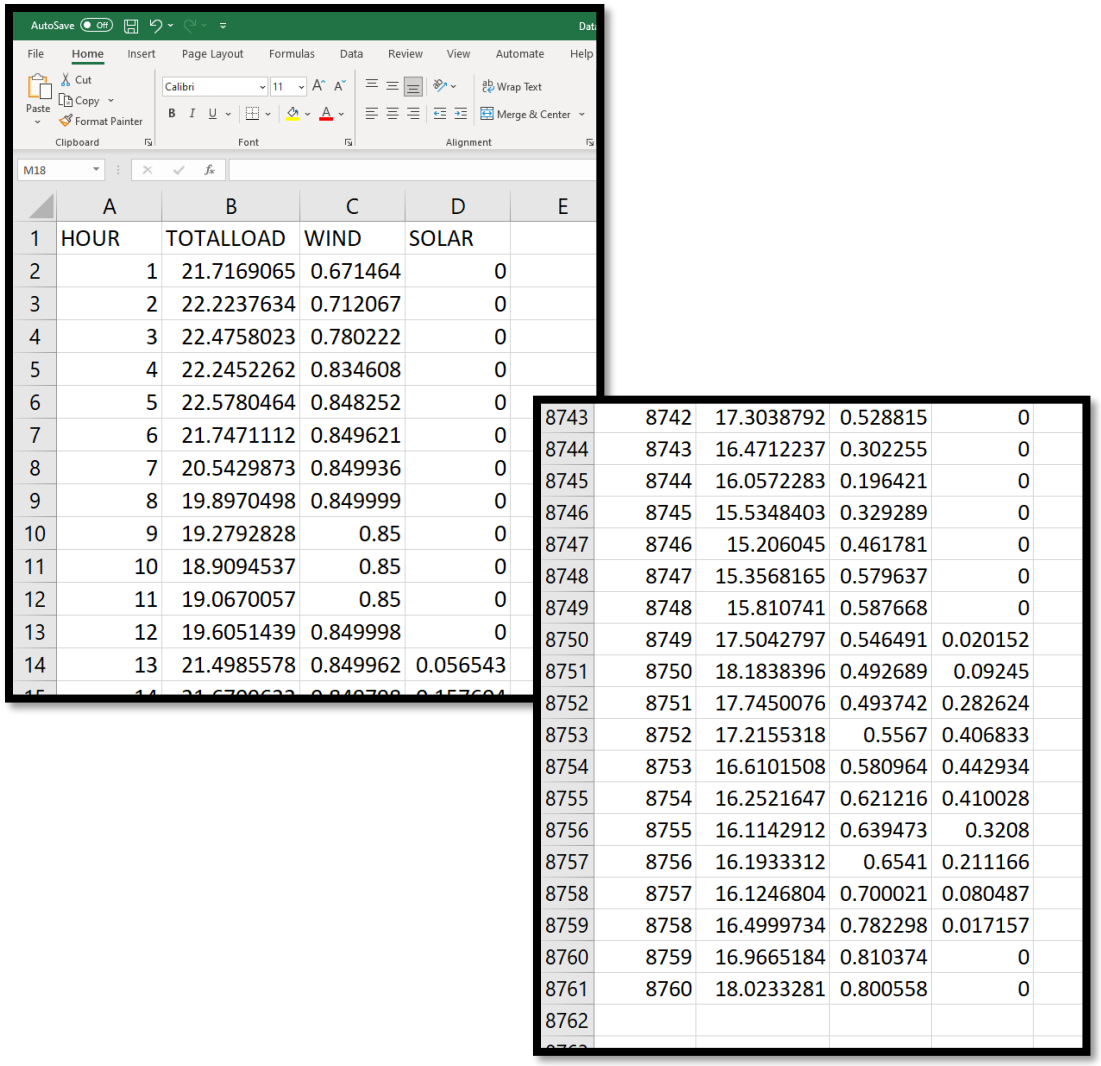
Market and Weather Scenarios

HERON\tests\integration_tests\ARMA\NYISO\Data_0.csv



	A	B	C	D	E
1	HOUR	TOTALLOAD	WIND	SOLAR	
2	1	21.7169065	0.671464	0	
3	2	22.2237634	0.712067	0	
4	3	22.4758023	0.780222	0	
5	4	22.2452262	0.834608	0	
6	5	22.5780464	0.848252	0	
7	6	21.7471112	0.849621	0	
8	7	20.5429873	0.849936	0	
9	8	19.8970498	0.849999	0	
10	9	19.2792828	0.85	0	
11	10	18.9094537	0.85	0	
12	11	19.0670057	0.85	0	
13	12	19.6051439	0.849998	0	
14	13	21.4985578	0.849962	0.056543	

8743	8742	17.3038792	0.528815	0
8744	8743	16.4712237	0.302255	0
8745	8744	16.0572283	0.196421	0
8746	8745	15.5348403	0.329289	0
8747	8746	15.206045	0.461781	0
8748	8747	15.3568165	0.579637	0
8749	8748	15.810741	0.587668	0
8750	8749	17.5042797	0.546491	0.020152
8751	8750	18.1838396	0.492689	0.09245
8752	8751	17.7450076	0.493742	0.282624
8753	8752	17.2155318	0.5567	0.406833
8754	8753	16.6101508	0.580964	0.442934
8755	8754	16.2521647	0.621216	0.410028
8756	8755	16.1142912	0.639473	0.3208
8757	8756	16.1933312	0.6541	0.211166
8758	8757	16.1246804	0.700021	0.080487
8759	8758	16.4999734	0.782298	0.017157
8760	8759	16.9665184	0.810374	0
8761	8760	18.0233281	0.800558	0
8762				

- Normally, pre-HERON steps include training an ARMA model
  - Some RAVEN-trained models included
- NYISO data for **Load**, **Wind**, **Solar**
  - **Load**: [GW]
  - **Wind**, **Solar**: [unitless fraction]

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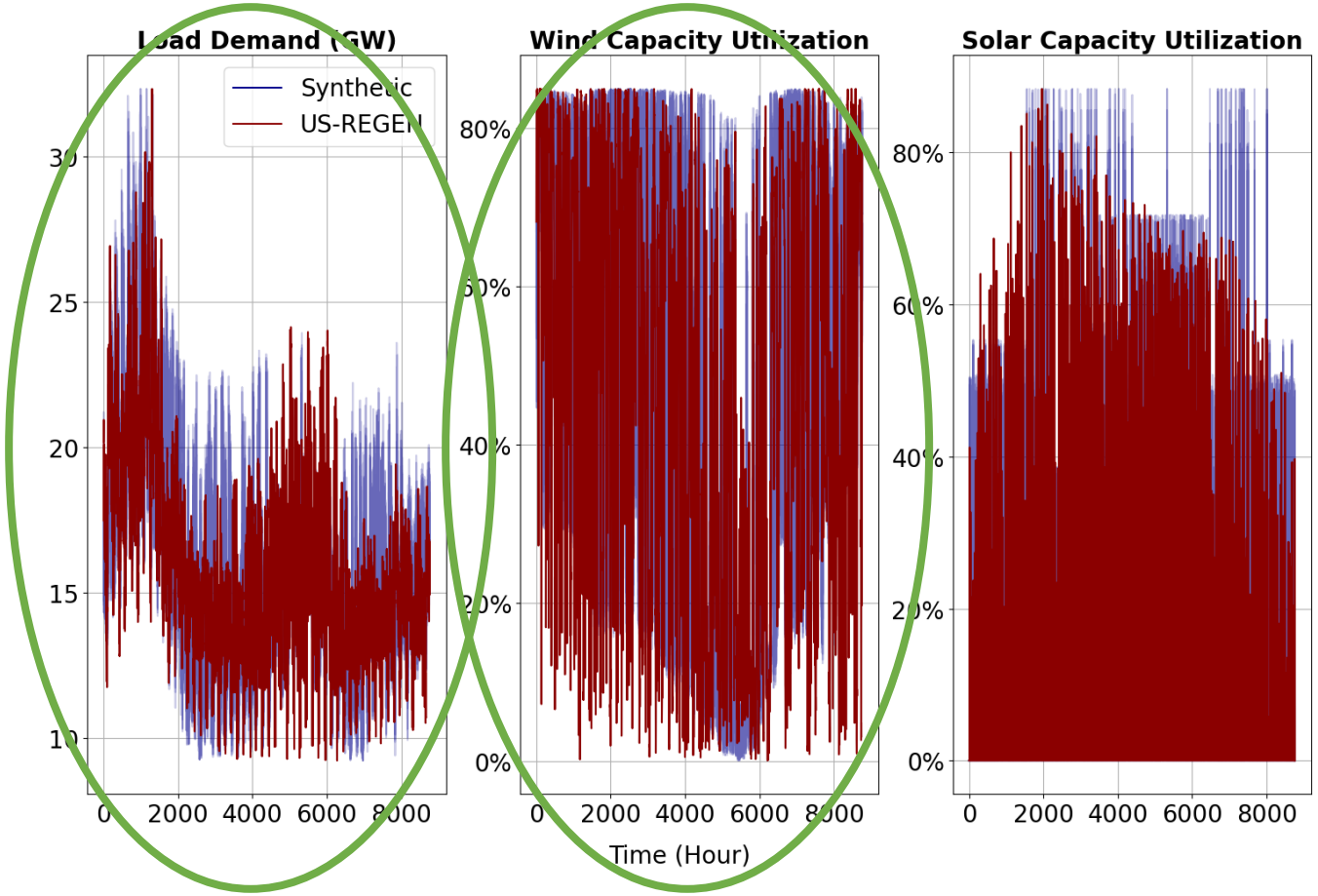
Market and Weather Scenarios

`HERON\tests\integration_tests\ARMA\NYISO\Data_0.csv`



- ARMA is trained by segmenting full dataset
- 1 year of data broken down into:
  - 2 representative clusters
  - each 24 hours long
- These are parameters decided by the users, kept simple here

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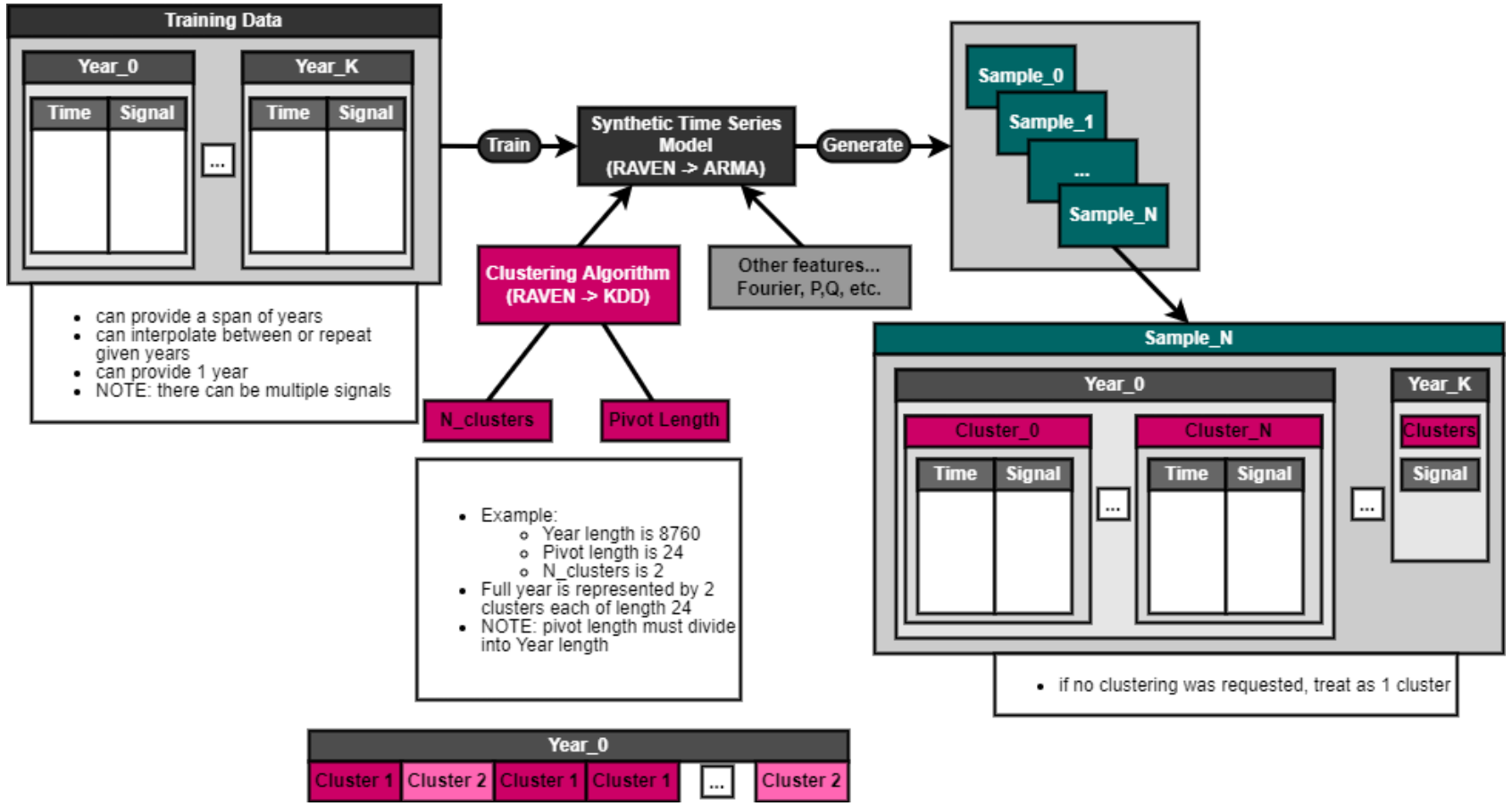
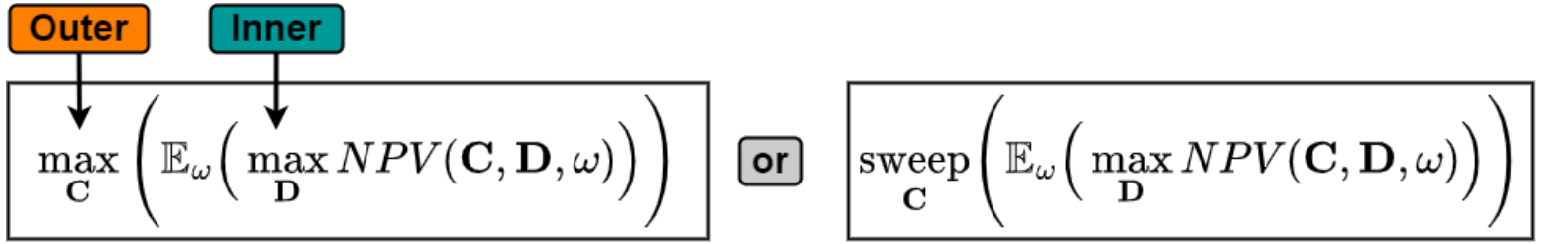
HERON Workflow

- All the hard work has already been done!
- From our given ARMA, synthetic histories will:
  - Contain a single year
    - Contain two clusters per year
      - Contain three signals per cluster (Load, Wind, ~~Solar~~)
      - Contain 24 time points per signal
  - For a multi-year simulation, HERON can repeat yearly data



HERON Workflow

- Two-stage optimization or sweep:
  - **Outer**: optimizing component capacities using RAVEN Gradient Descent
  - **Inner**: optimizing dispatch of resources using Pyomo and requested solver
    - GNU Linear Programming Kit [glpk]
    - Coin-or Branch-and-cut [cbc]
    - Interior Point Optimizer [ipopt]



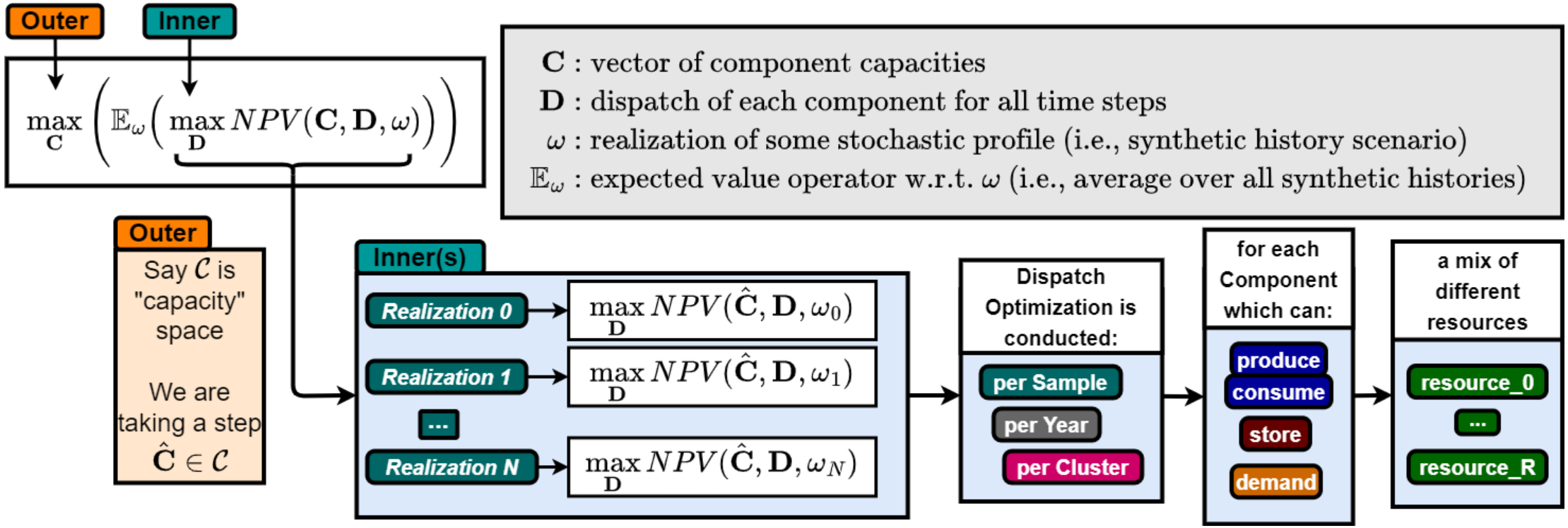
$\mathbf{C}$: component capacities
$\mathbf{D}$: dispatch of each component for all time steps
ω : realization of some stochastic profile (i.e., synthetic history scenario)
$\mathbb{E}_\omega$: expected value operator w.r.t. ω (i.e., average over all synthetic histories)

Modified from:

A. Epiney, C. Rabiti, P. Talbot, A. Alfonsi, "Economic analysis of a nuclear hybrid energy system in a stochastic environment including wind turbines in an electricity grid" *Applied Energy* (2020)

IES Integrated Energy Systems

HERON Workflow



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HERON Input Script

- Case

HERON\tests\workshop\wind\heron_input.xml

```
13    <Case name="npp_wind">
14      <mode>sweep</mode>
15      <!-- Uncomment below to run in debug mode! -->
16      <!-- <debug/> -->
17      <num_arma_samples>20</num_arma_samples>
18      <time_discretization>
19        <year_variable>YEAR</year_variable>
20        <time_variable>HOUR</time_variable>
21        <end_time>23</end_time>
22        <num_steps>24</num_steps>
23      </time_discretization>
24      <economics>
25        <ProjectTime>3</ProjectTime>
26        <DiscountRate>0.08</DiscountRate>
27        <tax>0.1</tax>
28        <inflation>0.1</inflation>
29        <verbosity>50</verbosity>
30      </economics>
31      <dispatcher>
32        <pyomo/>
33      </dispatcher>
34    </Case>
```

- `num_arma_samples = 20`
  - 20 inner samples used to get expected value of metric (NPV) in **Outer**
- `ProjectTime= 3`
  - Each inner sample simulates 3 project years
- `<time_discretization>`
  - Each cluster/segment has 24 time steps
- NOTE: clusters/segments automatically read from ARMA

HERON Input Script

- Components: Wind

HERON\tests\workshop\wind\heron_input.xml

```
38    <Component name="wind">
39      <produces resource="electricity" dispatch="independent">
40        <capacity resource="electricity">
41          <sweep_values debug_value="30">0, 10, 30, 50, 70, 90</sweep_values> <!-- CHANGE THE DEBUG VALUE -->
42        </capacity>
43        <capacity_factor>
44          <ARMA variable="WIND">synth</ARMA>
45        </capacity_factor>
46      </produces>
47      <economics>
48        <lifetime>5</lifetime>
49        <CashFlow name="capex" type="one-time" taxable="True" inflation="none" mult_target="False">
50          <driver>
51            <variable>wind_capacity</variable>
52          </driver>
53          <reference_price>
54            <!-- 1470 $/kW * 1e6 kW/GW = 1.47e9 est cost for 1 GW wind -->
55            <!-- adjust for short project length-->
56            <fixed_value>-1.47e8</fixed_value>
57          </reference_price>
58        </CashFlow>
59      </economics>
60    </Component>
```

- `<capacity>`
  - This is the rated capacity of the Wind Farm
  - Currently, we sweep through some values
    - Can be fixed, opt, etc.
- `<capacity_factor>`
  - Actual usage of capacity per unit time
  - Using synthetic histories

NPP and Wind

Let’s run some simulations!

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Running in Debug Mode

1. Uncomment `<debug>` line
   - Note that this overrides some parameters
     - Only using 1 sample
     - Only using 1 year
2. Change debug values!
   - HERON only use these in **debug** mode, overrides sweep values

HERON\tests\workshop\wind\heron_input.xml

```
13    <Case name="npp_wind">
14      <mode>sweep</mode>
15      <!-- Uncomment below to run in debug mode! -->
16      <!-- <debug/> -->
17      <num_arma_samples>20</num_arma_samples>
18      <time_discretization>
```

```
37      <Component name="wind">
38        <produces resource="electricity" dispatch="independent">
39          <capacity resource="electricity">
40            <!-- CHANGE THE DEBUG VALUE -->
41            <sweep_values debug_value="0">0, 10, 30, 50, 70, 90</sweep_values>
42            <multiplier>1</multiplier>
43          </capacity>
```

```
65      <Component name="npp">
66        <produces resource="electricity" dispatch="fixed">
67          <capacity resource="electricity">
68            <!-- CHANGE THE DEBUG VALUE -->
69            <sweep_values debug_value="20">0, 20, 40, 60</sweep_values>
70          </capacity>
```

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Running in Debug Mode

- Run HERON, then outer.xml:

```
../../../heron heron_input.xml

../../../../raven/raven_framework outer.xml
```

- Things to try in debug mode:
  1) Wind = 0; NPP = 20
  2) Wind = 10; NPP = 20
  3) Switch NPP to `dispatch="independent"` or `dispatch="fixed"`
- Pause here – Check Network plot!

HERON\tests\workshop\wind\heron_input.xml

```
13    <Case name="npp_wind">
14      <mode>sweep</mode>
15      <!-- Uncomment below to run in debug mode! -->
16      <!-- <debug/> -->
17      <num_arma_samples>20</num_arma_samples>
18      <time_discretization>
```

```
37      <Component name="wind">
38        <produces resource="electricity" dispatch="independent">
39          <capacity resource="electricity">
40            <!-- CHANGE THE DEBUG VALUE -->
41            <sweep_values debug_value="0">0, 10, 30, 50, 70, 90</sweep_values>
42            <multiplier>1</multiplier>
43          </capacity>
```

```
65      <Component name="npp">
66        <produces resource="electricity" dispatch="fixed">
67          <capacity resource="electricity">
68            <!-- CHANGE THE DEBUG VALUE -->
69            <sweep_values debug_value="20">0, 20, 40, 60</sweep_values>
70          </capacity>
```

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Running in Debug Mode

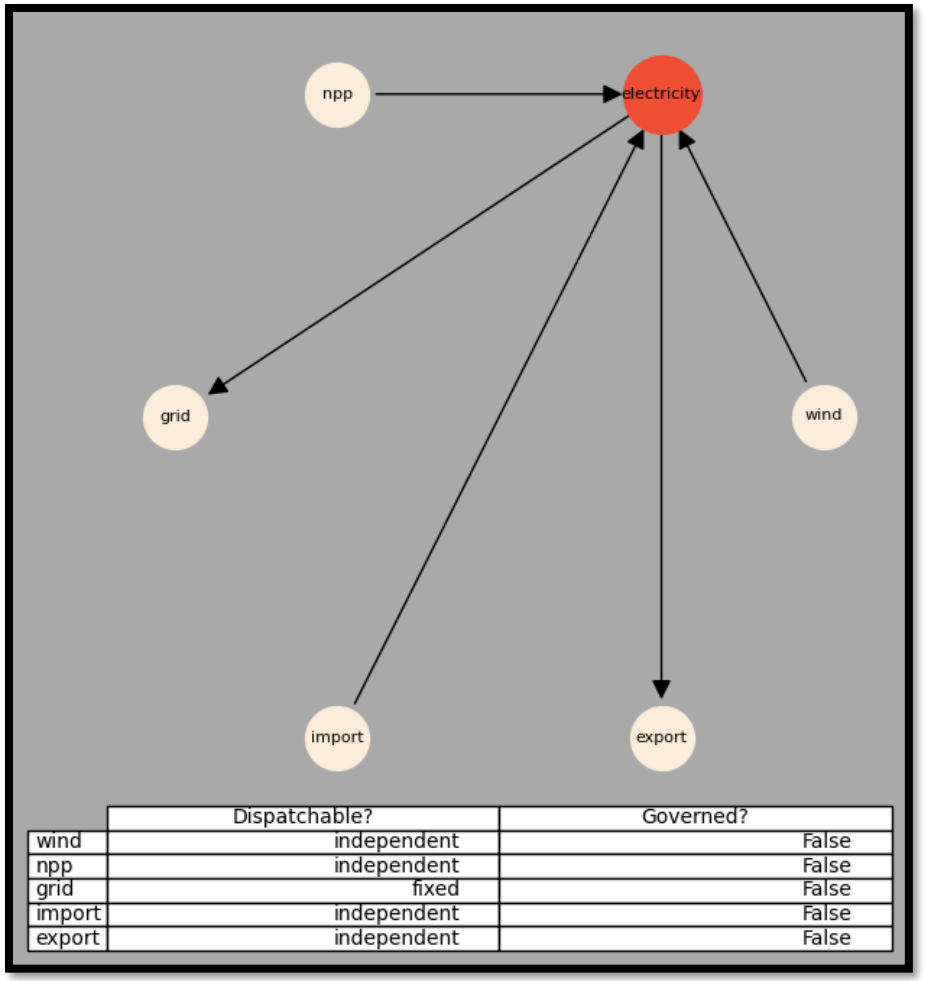
- Run HERON, then outer.xml:

```
../../../heron heron_input.xml

../../../../raven/raven_framework outer.xml
```

- Things to try in debug mode:
  1) Wind = 0; NPP = 20
  2) Wind = 10; NPP = 20
  3) Switch NPP to `dispatch="independent"` or `dispatch="fixed"`

HERON\tests\workshop\wind\network.png



	Dispatchable?	Governed?
wind	independent	False
npp	independent	False
grid	fixed	False
import	independent	False
export	independent	False

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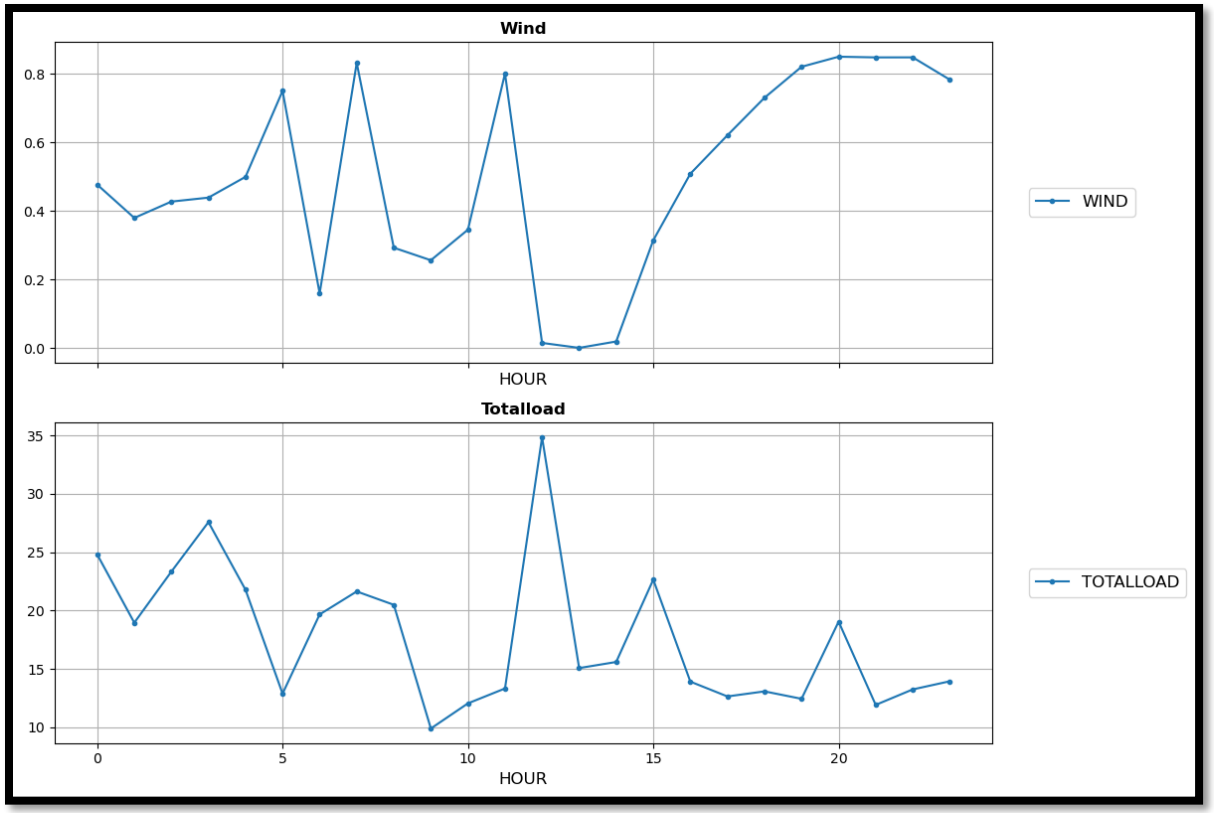
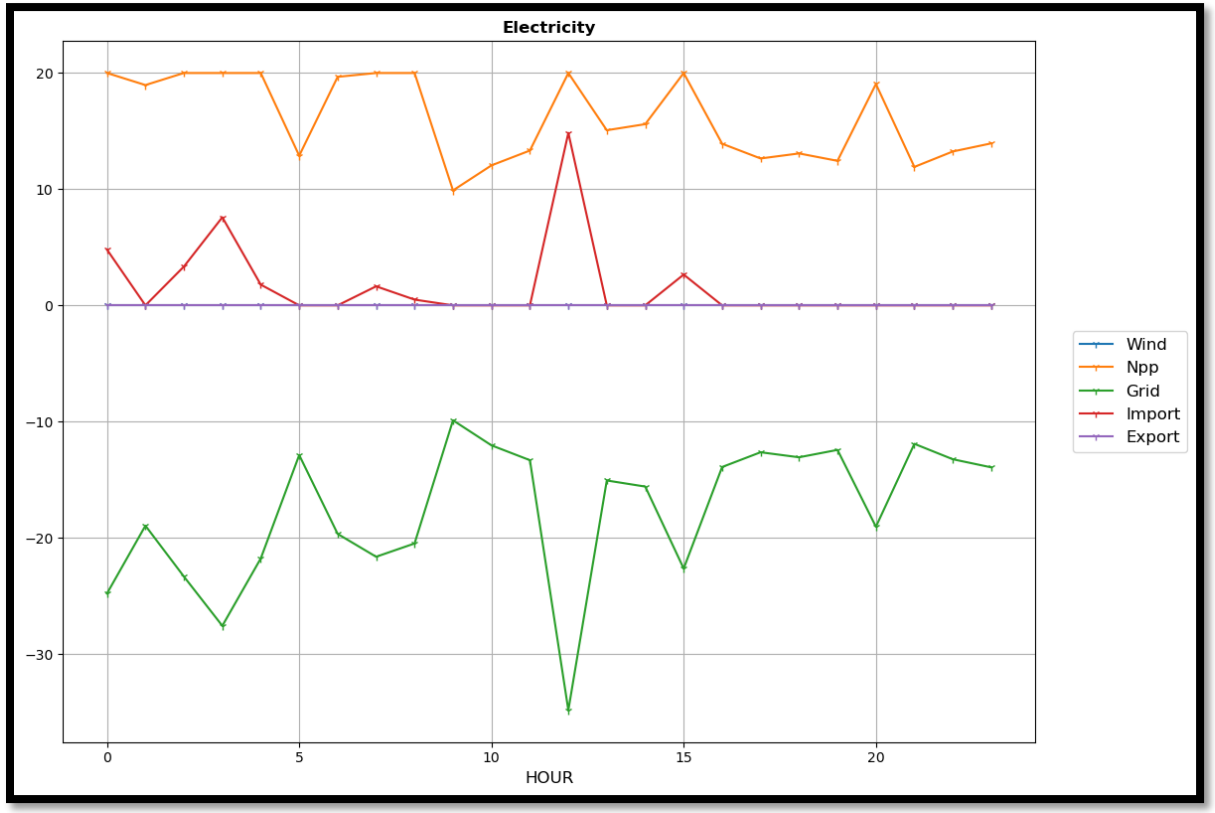
Running in Debug Mode

`HERON\tests\workshop\wind\npp_wind_o`

Stochastic History for Single Cluster



Dispatch of Electricity



Wind = 0GW

NPP = 20GW, independent dispatch

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Doing a Full Sweep

- Run HERON, then outer.xml:

```
../../../heron heron_input.xml

../../../../raven/raven_framework outer.xml
```

- Things to change:
  1) Comment out the <debug/> line
  2) Input desired sweep values for:
     - Wind Capacities
     - NPP Capacities

- Pause here

HERON\tests\workshop\wind\heron_input.xml

```
13    <Case name="npp_wind">
14      <mode>sweep</mode>
15      <!-- Uncomment below to run in debug mode! -->
16      <!-- <debug/> -->
17      <num_arma_samples>20</num_arma_samples>
18      <time_discretization>
19        <year_variable>YEAR</year_variable>
20        <time_variable>HOUR</time_variable>
21        <end_time>23</end_time>
```

```
37      <Component name="wind">
38        <produces resource="electricity" dispatch="independent">
39          <capacity resource="electricity">
40            <!-- CHANGE THE DEBUG VALUE -->
41            <sweep_values debug_value="0">0, 10, 30, 50, 70, 90</sweep_values>
42            <multiplier>1</multiplier>
43          </capacity>
```

```
65      <Component name="npp">
66        <produces resource="electricity" dispatch="fixed">
67          <capacity resource="electricity">
68            <!-- CHANGE THE DEBUG VALUE -->
69            <sweep_values debug_value="20">0, 20, 40, 60</sweep_values>
```

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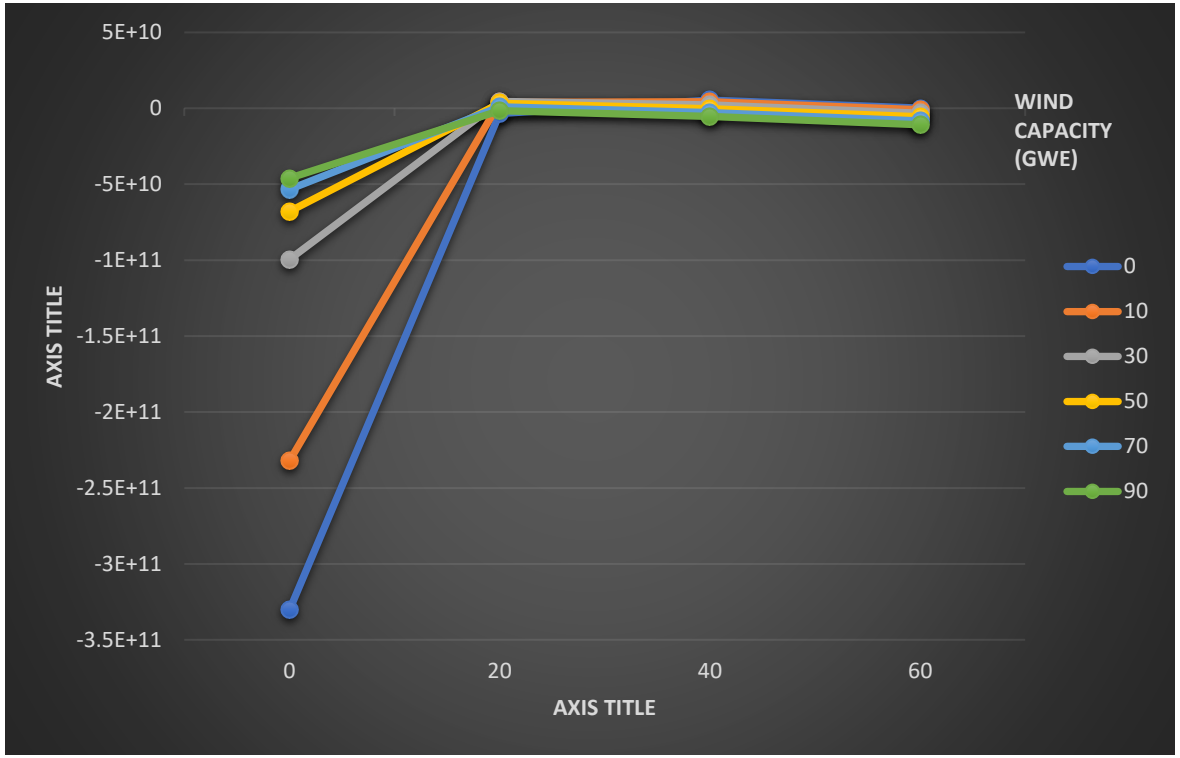
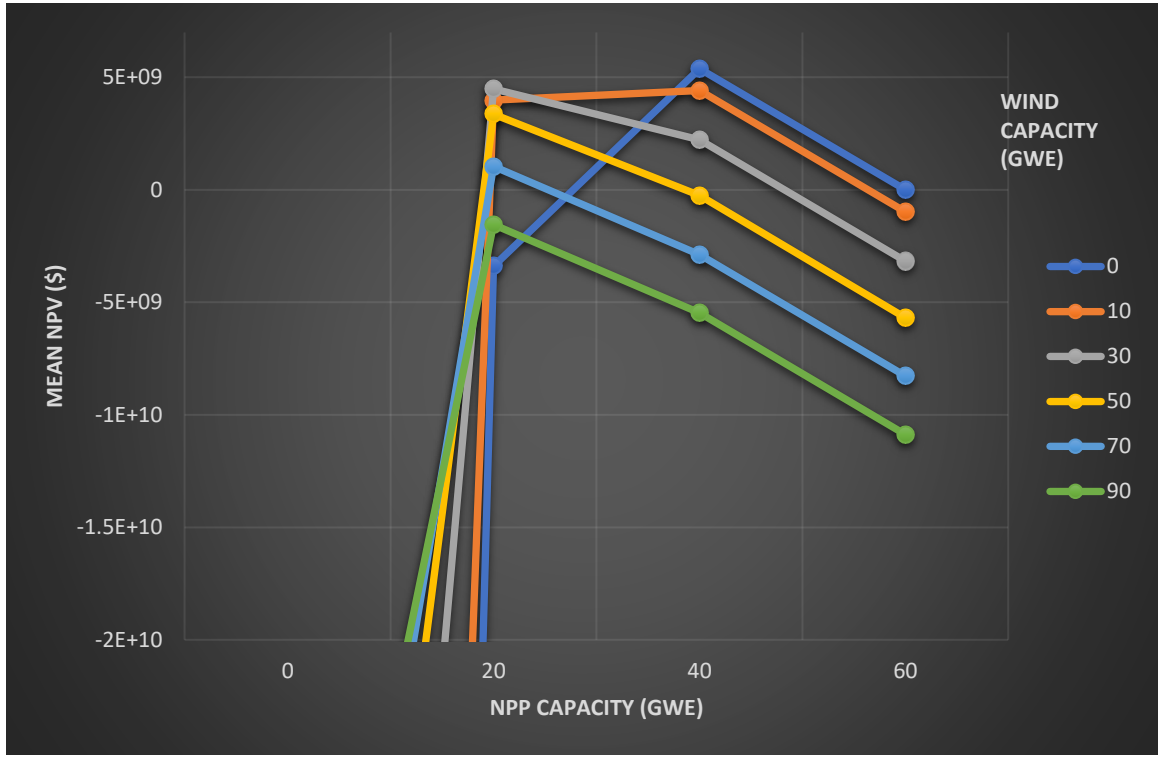
Doing a Full Sweep

Results!





Zoomed-in plot

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- After running in debug mode and getting a coarse look via sweep runs, might be time for an optimization run
  - Will take a while depending on computation resources
  - best to do on your own or on High Performance Computing (HPC) machines

- Fun things to toggle—How do these affect NPV?:
  - Project time > 3 years
  - Project time > component lifetimes
  - Add depreciation to components

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NPP and Wind With Storage

Even Stronger with Arbitrage!

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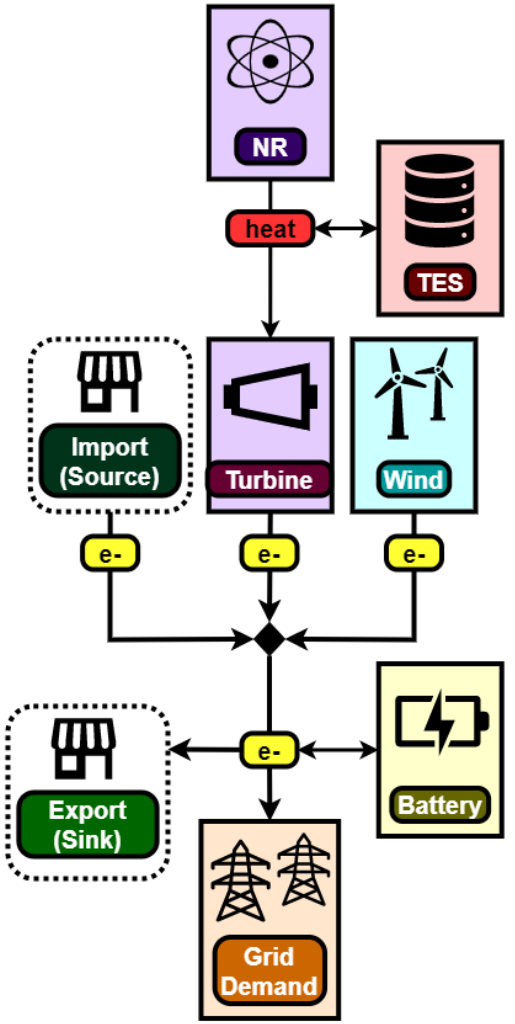
Basic Schematic of IES

- **Nuclear Power Plant:**
  - **Nuclear Reactor**
    - Is now decoupled from electricity generation
    - Produces heat that can be converted to electricity
  - **Turbine**
    - Converts heat into electricity via a transfer function (η= 0.33)
- **Thermal Energy Storage (TES)**
  - Storage unit that can charge with heat and discharge via some dispatch strategy



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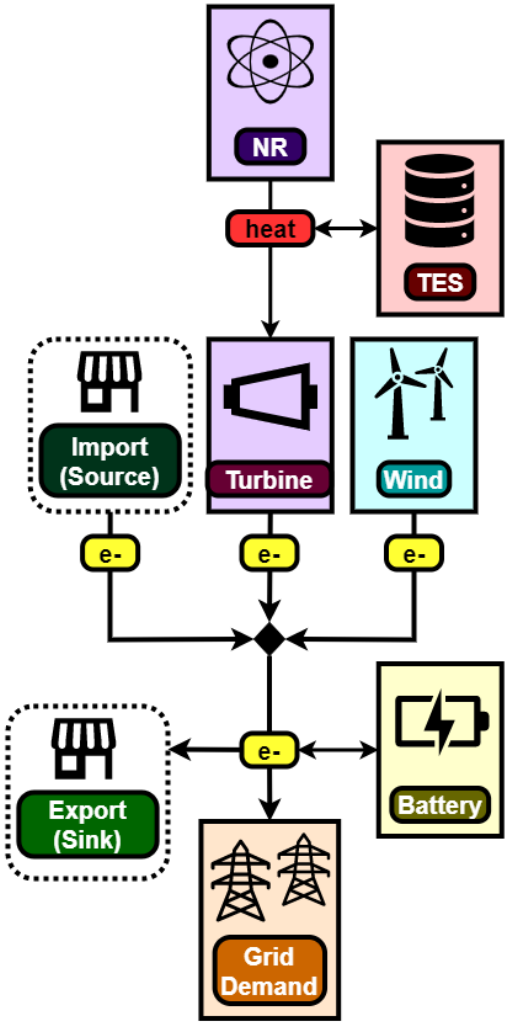
Basic Schematic of IES

- **Wind Farm**
  - Also has rated capacity, but varies based on wind speeds
    - Capacity factor taken from synthetic histories
- **Battery**
  - Storage for electricity resource
- **Electricity Grid**
  - Demand
    - also taken from synthetic histories
  - External Market (Source/Sink)



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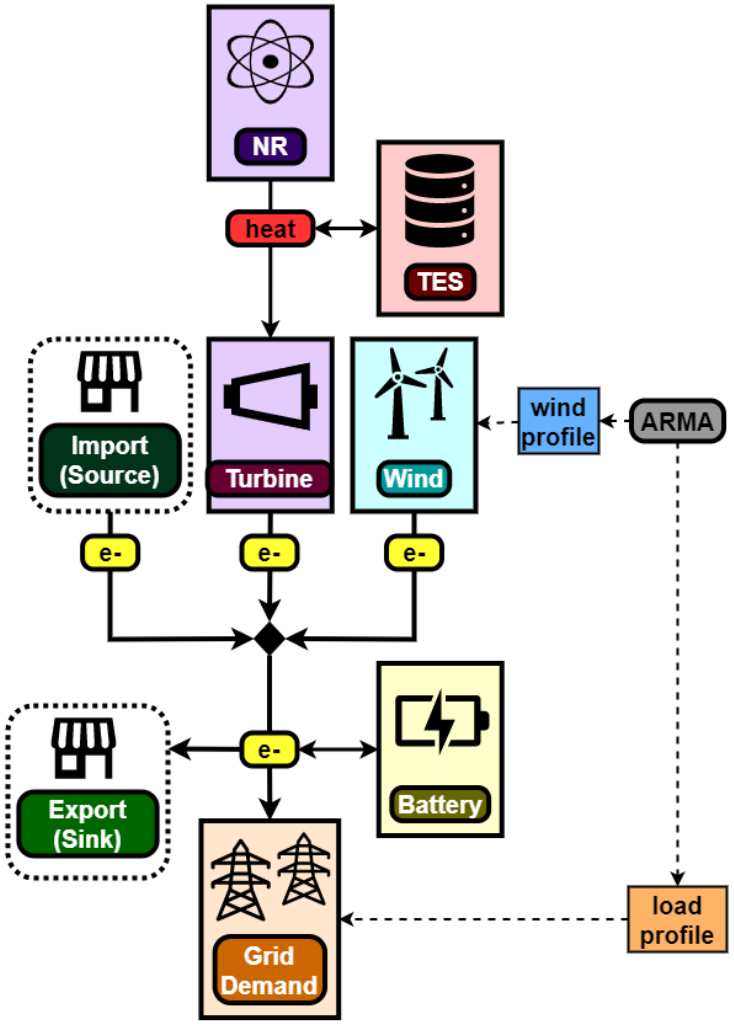
Basic Schematic of IES

- **Given:**
  - IES (NPP + ***TES*** + Wind Farm + ***Battery***)
  - Market and Geographic Region
- **Need to find:**
  - Capacities
  - Dispatch strategies
- **Goal(s):**
  - Satisfy demand
  - Minimize costs/maximize profits (NPV)
- **Recall:**
  - Load profiles and weather contain uncertainty
  - Uncertainty represented using synthetic time histories (ARMA)



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HERON Input Script

`HERON\tests\workshop\wind\heron_input_storage.xml`

```
123       <Component name="turbine">
124         <produces resource="electricity" dispatch="dependent">
125           <consumes>heat</consumes>
126           <capacity resource="electricity">
127             <fixed_value>200</fixed_value>
128           </capacity>
129           <transfer>
130             <linear>
131               <rate resource="heat">-1</rate>
132               <rate resource="electricity">0.5</rate>  <!-- Efficiency Term (MWe/MWt)-->
133             </linear>
134           </transfer>
135         </produces>
```

Efficiency

Different resource

```
63      <Component name="reactor">
64        <produces resource="heat" dispatch="independent"> <!-- TRY first with fixed dispatch-->
65          <capacity resource="heat">
66            <sweep_values debug_value="20">0, 50</sweep_values> <!-- CHANGE THE DEBUG VALUE; ADD MORE! -->
67          </capacity>
68        </produces>
69        <economics>
70          <lifetime>10</lifetime>
71          <CashFlow name="capex" type="one-time" taxable="True" inflation="none" mult_target="False">
72            <driver>
73              <variable>reactor_capacity</variable>
74            </driver>
75            <reference_price>
76              <!-- $3000/kWe * 1e6 kW/GW, but note reduced project length -->
77              <fixed_value>-3e8</fixed_value>
78              <multiplier>0.5</multiplier> <!-- Efficiency Term (MWe/MWt)-->
79            </reference_price>
80          </CashFlow>
81          <CashFlow name="var_OM" type="repeating" taxable='True' inflation='none' mult_target='False'>
82            <driver>
83              <activity>heat</activity>
84              <multiplier>-1</multiplier>
85            </driver>
86            <reference_price>
87              <!-- ballpark $/MWhe -->
88              <!-- https://www.lazard.com/media/451086/lazard-levelized-cost-of-energy-version-130-vf.pdf -->
89              <fixed_value>3.5e3</fixed_value>
90              <multiplier>0.5</multiplier> <!-- Efficiency Term (MWe/MWt)-->
91            </reference_price>
92          </CashFlow>
93        </economics>
94      </Component>
```

Efficiency

- **Turbine** converts heat to electricity
  - Linear transfer rate – efficiency
  - Dispatch is “dependent”
    - Capacity large enough to take in NPP and TES production
- **Reactor** generates heat
  - Keeping previous costs ($/GWe)
  - Efficiency used as multiplier (GWt/GWe)

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HERON Input Script

HERON\tests\workshop\wind\heron_input_storage.xml

```
97      <Component name="tes">
98        <stores resource="heat" dispatch="independent">
99          <capacity resource="heat">
100           <sweep_values debug_value="30">0, 10</sweep_values> <!-- CHANGE THE DEBUG VALUE;
101         </capacity>
102         <initial_stored>
103           <fixed_value>0.01</fixed_value>
104         </initial_stored>
105       </stores>
106       <economics>
```

```
141     <Component name="battery">
142       <stores resource="electricity" dispatch="independent">
143         <capacity resource="electricity">
144           <sweep_values debug_value="30">0, 5</sweep_values>
145         </capacity>
146         <initial_stored>
147           <fixed_value>0.01</fixed_value>
148         </initial_stored>
149       </stores>
150       <economics>
```

- **TES** stores heat
  - Assuming only CAPEX (capital expenditures) cost
    - $30/MWt
- **Battery** stores electricity
  - Assuming only CAPEX (capital expenditures) cost
    - $151/MWe

IES Integrated Energy Systems

Running in Debug Mode

- Run HERON, then outer.xml:

```
../../../heron heron_input_storage.xml

../../../../raven/raven_framework outer.xml
```

- Things to try in debug mode:
  1) Component sizes:
     - Wind = 30; Reactor = 20
     - TES = 30; Battery = 30
  2) Switch Reactor to `dispatch="independent"` or `dispatch="fixed"`
- Pause here – Check Network plot!

HERON\tests\workshop\wind\heron_input_storage.xml

```
13      <Case name="npp_wind_storage">
14        <mode>sweep</mode>
15        <!-- Uncomment below to run in debug mode! -->
16        <!-- <debug/> -->
17        <num_arma_samples>20</num_arma_samples>
18        <time_discretization>
```

```
38      <Component name="wind">
39        <produces resource="electricity" dispatch="independent">
40          <capacity resource="electricity">
41            <sweep_values debug_value="10">0, 15</sweep_values>
42          </capacity>
```

```
63      <Component name="reactor">
64        <produces resource="heat" dispatch="independent"> <!-- T
65          <capacity resource="heat">
66            <sweep_values debug_value="20">0, 50</sweep_values>
67          </capacity>
```

```
97      <Component name="tes">
98        <stores resource="heat" dispatch="independent">
99          <capacity resource="heat">
100           <sweep_values debug_value="5">0, 10</sweep_values>
101         </capacity>
```

```
141     <Component name="battery">
142       <stores resource="electricity" dispatch="independent">
143         <capacity resource="electricit">
144           <sweep_values debug_value="2">0, 5</sweep_values>
145         </capacity>
```

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Running in Debug Mode

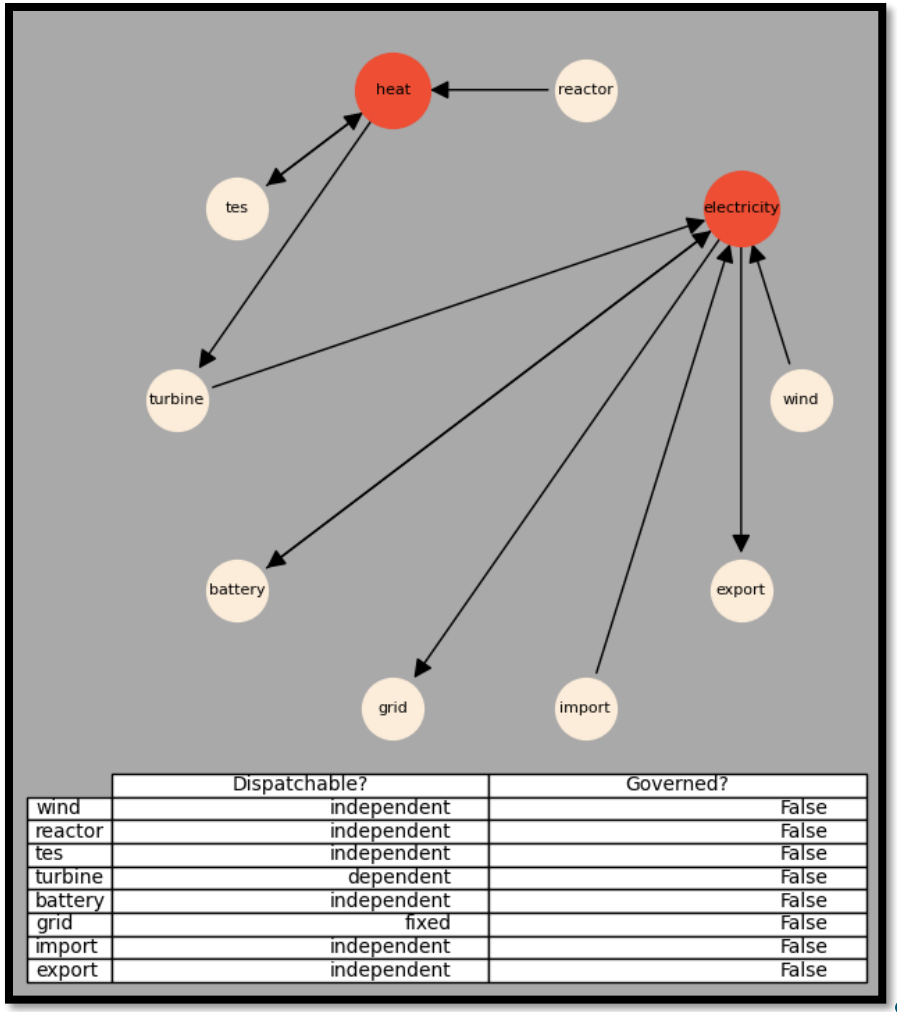
- Run HERON, then outer.xml:

```
../../../heron heron_input_storage.xml

../../../../raven/raven_framework outer.xml
```

- Things to try in debug mode:
  1) Component sizes:
     - Wind = 30; Reactor = 20
     - TES = 30; Battery = 30
  2) Switch Reactor to `dispatch="independent"` or `dispatch="fixed"`

HERON\tests\workshop\wind\network.png



	Dispatchable?	Governed?
wind	independent	False
reactor	independent	False
tes	independent	False
turbine	dependent	False
battery	independent	False
grid	fixed	False
import	independent	False
export	independent	False

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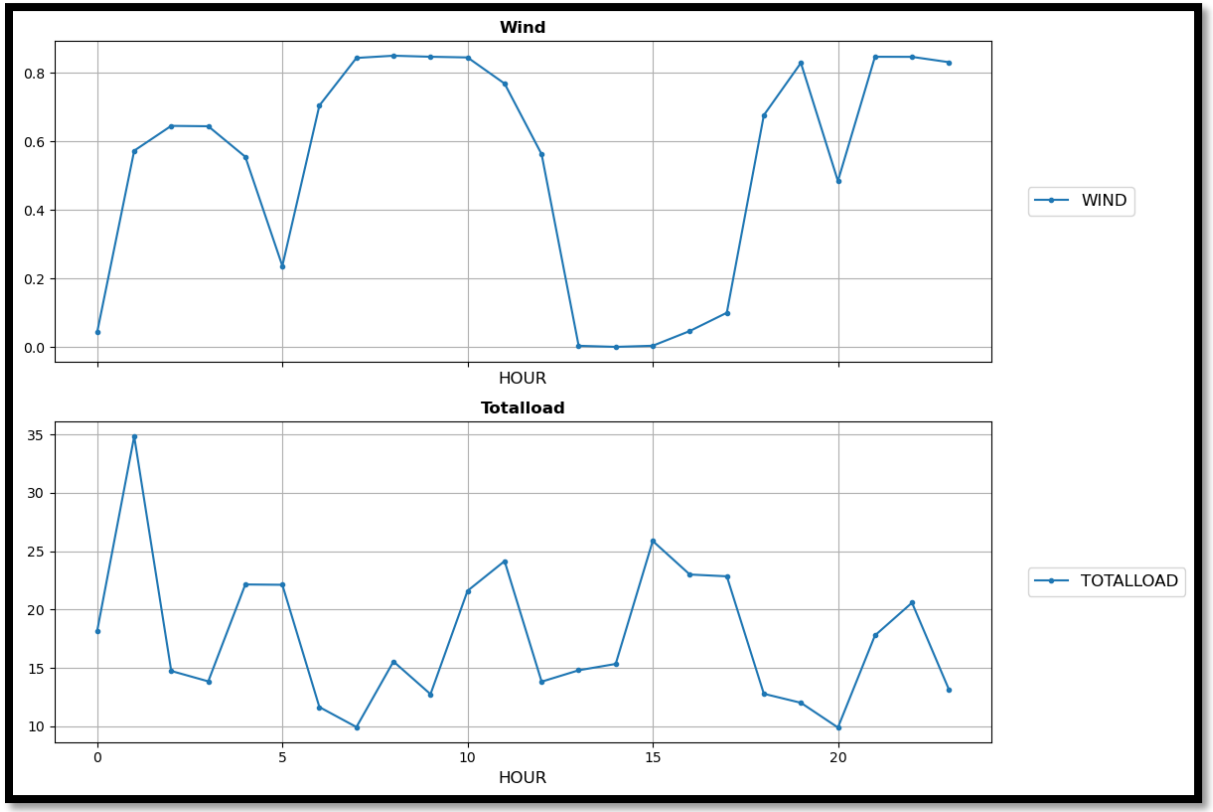
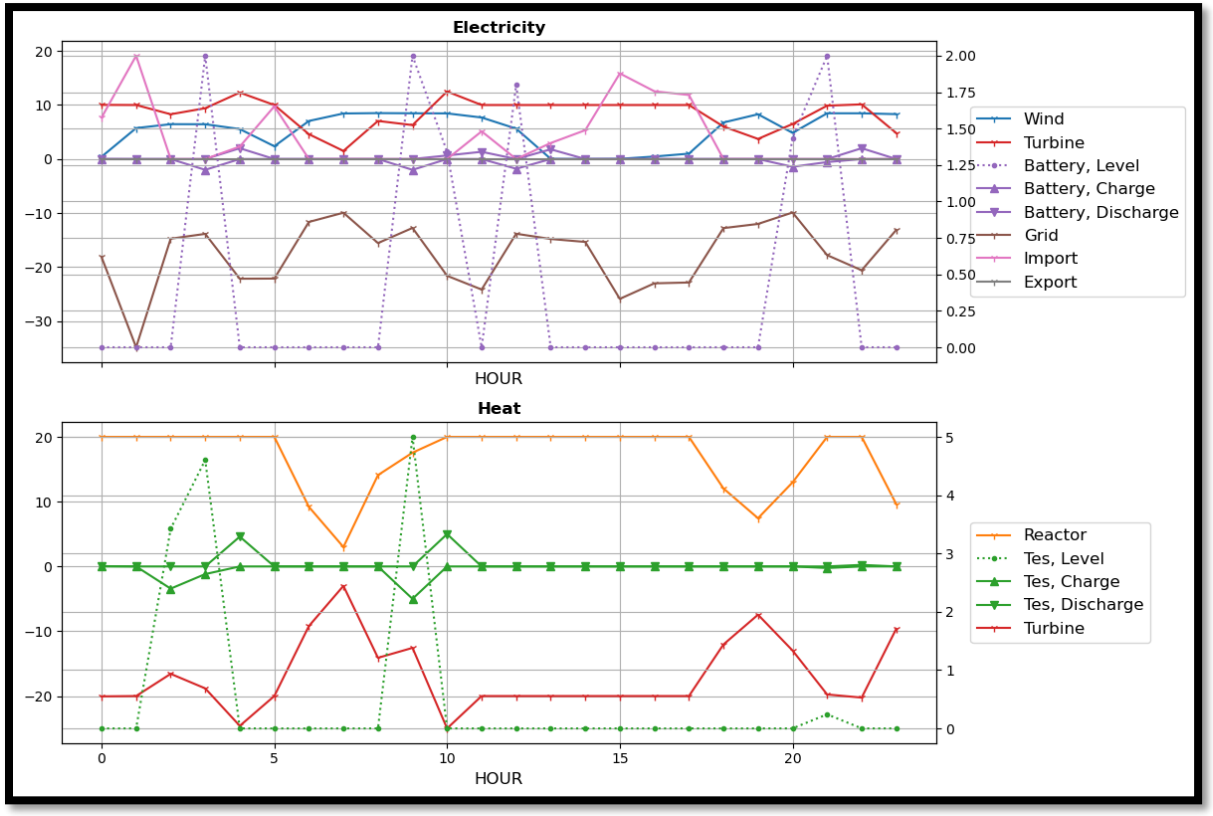
Running in Debug Mode

`HERON\tests\workshop\wind\npp_wind_storage_o`

Stochastic History for Single Cluster



Dispatch of Heat and Electricity



Wind = 10 Gwe
Reactor = 20 GWt (independent dispatch)
TES = 5 GWt
Battery = 2 GWe

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Doing a Full Sweep

- Run HERON, then outer.xml:

```
../../../heron heron_input_storage.xml

../../../../raven/raven_framework outer.xml
```

- Things to change:
  1) Comment out the <debug/> line
  2) Input desired sweep values for:
     - Wind Capacity
     - Reactor Capacity
     - TES Capacity
     - Battery Capacity

HERON\tests\workshop\wind\heron_input_storage.xml

```
13    <Case name="npp_wind_storage">
14      <mode>sweep</mode>
15      <!-- Uncomment below to run in debug mode! -->
16      <!-- <debug/> -->
17      <num_arma_samples>20</num_arma_samples>
18      <time_discretization>
```

```
37    <Components>
38      <Component name="wind">
39        <produces resource="electricity" dispatch="independent">
40          <capacity resource="electricity">
41            <sweep_values debug_value="30">0, 15</sweep_values>
42          </capacity>
```

```
63      <Component name="reactor">
64        <produces resource="heat" dispatch="independent">
65          <capacity resource="heat">
66            <sweep_values debug_value="20">0, 50</sweep_values>
67          </capacity>
```

```
97      <Component name="tes">
98        <stores resource="heat" dispatch="independent">
99          <capacity resource="heat">
100           <sweep_values debug_value="30">0, 10</sweep_values>
101         </capacity>
```

```
141     <Component name="battery">
142       <stores resource="electricity" dispatch="independent">
143         <capacity resource="electricity">
144           <sweep_values debug_value="30">0, 5</sweep_values>
145         </capacity>
```

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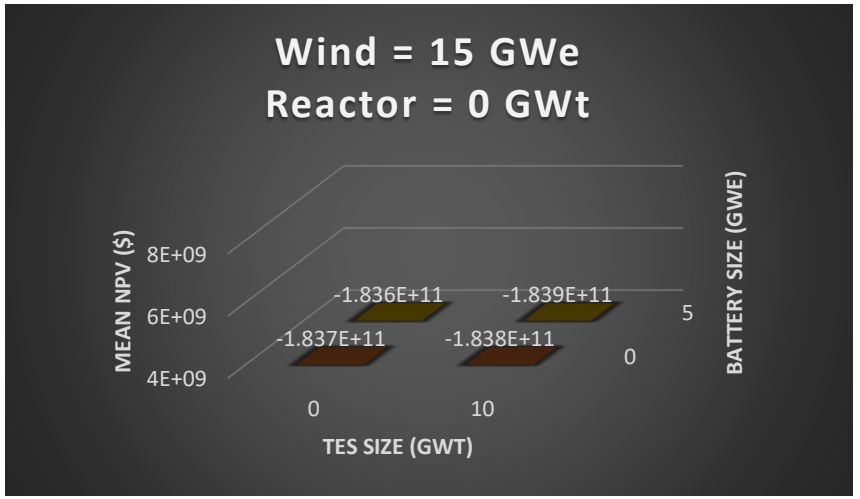
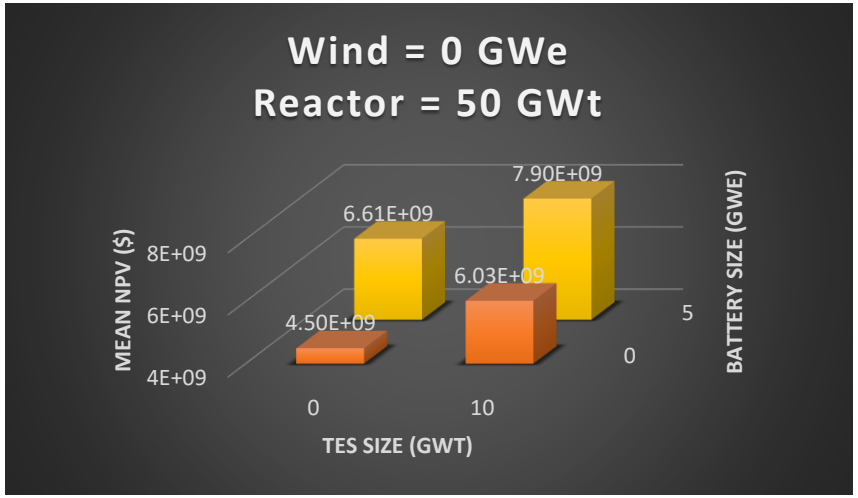
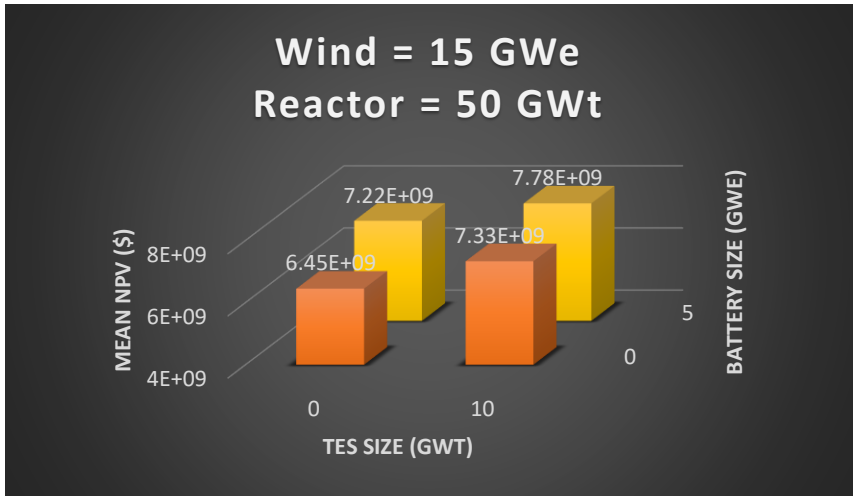
Doing a Full Sweep

- Some results from multi-dimensional results
- Try different sweep values!
  - Fixed Reactor output
  - Higher Grid Demand







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