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FORCE Development Status Update: Vertical Integration and Benchmarking of System Dynamics

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ABSTRACT

Recent efforts to establish effective models for grid energy analysis, especially given the increase in variable renewable energy (VRE) sources and the economic challenges faced by traditional nuclear energy, have generated new technological considerations. One effort to improve the economic viability of nuclear power involves investigating integrated energy systems (IES) which include secondary energy systems that introduce flexibility and secondary market possibilities to existing and perceived future nuclear energy generation technologies. To analyze the technical and economic potential of IES, the Framework for Optimization of Resources and Economics (FORCE) tool suite was developed through a collaboration among national laboratories. Within the FORCE tool suite, the Holistic Energy Resource Optimization Network (HERON) provides algorithms for analyzing the long-term viability of potential IES technologies, while HYBRID provides algorithms and models to achieve high-resolution analysis of coupling physics over a short time period.

Continued maturing of the FORCE tool suite requires further interconnections between the various tools in the suite in order to ensure consistent analysis. Analyses performed by applying HYBRID to transient process modeling should be easily harvestable as inputs to HERON analyses. The first item in this status update is a demonstration of an automated data pipeline for loading data from HYBRID into HERON analyses.

Application of HYBRID results to HERON, as part of using the FORCE tool suite, relies on robust modeling assumptions for the various models included in HYBRID. The second result of this status update is the benchmarking and validation of cost and operational data, with a particular focus on natural gas energy generators. These generators are benchmarked with a focus on contrasting them with proposed thermal energy storage (TES) technologies.

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ACRONYMS

CAPEX	capital expenditures
CSV	comma-separated values
CAES	compressed air energy storage
CTES	concrete thermal energy storage
EIA	Energy Information Administration
XML	Extensible Markup Language
FOM	fixed operation and maintenance
FORCE	Framework for Optimization of Resources and Economics
HERON	Holistic Energy Resource Optimization Network
IES	integrated energy systems
NPP	nuclear power plant
SHS	sensible heat storage
SHTES	sensible heat thermal energy storage
TES	thermal energy storage
VOM	variable operation and maintenance
VRE	variable renewable energy

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1 INTRODUCTION

1.1 Background

Recent efforts to establish effective models for grid energy analysis, especially given the increase in variable renewable energy (VRE) sources and the economic challenges faced by traditional nuclear energy, have generated new technological considerations. One effort to improve the economic viability of nuclear power involves investigating integrated energy systems (IES) which include secondary energy systems that introduce flexibility and secondary market possibilities to existing and perceived future nuclear energy generation technologies. To analyze the technical and economic potential of IES, the Framework for Optimization of Resources and Economics (FORCE) tool suite was developed through a collaboration among national laboratories. Within the FORCE tool suite, the Holistic Energy Resource Optimization Network (HERON) provides algorithms for analyzing the long-term viability of potential IES technologies, while HYBRID provides algorithms and models to achieve high-resolution analysis of over a short time period.

1.2 Vertical Integration

In prior studies using FORCE, the analysis was divided into two distinct tasks. First, HYBRID models were developed and explored to determine the fundamental properties of generating units. These fundamental properties included transfer functions (the proportion of feedstock resources required to yield generated resources), operational ramping limitations (the limits to adjusting the generation rate over time), and economics (e.g., capital costs, fixed operational costs, and flexible operational costs). The analyst then manually transferred these fundamental properties from HYBRID to HERON for the second modeling task. The fundamental properties of generating units are used in HERON as constraints and economic drivers for long-term portfolio optimization based on stochastic scenarios and economic dispatch.

Whenever manual transfer of data is required, it introduces a source of error, whether in terms of typographical errors, misunderstanding of units, etc. Automation can mitigate such errors by ensuring that data are consistently and correctly transferred. In the case of HYBRID and HERON, the ability to automatically transfer fundamental component data from HYBRID to HERON limits the potential for errors in manual transfer, enabling analysts to focus more on analysis and less on clerical activities.

In this work, we demonstrate a pipeline for automatically loading some fundamental component data from HYBRID to HERON. This does not deliver a fully automated connection between the software tools; however, it demonstrates how such automation may be pursed in the future, and it provides proof of concept for such an activity.

1.3 Benchmarking and Model Comparison

For effective application to grid energy system analysis, models must be reliable and able to sufficiently reflect real operations. One consideration in deploying IES is the replacement of carbon-producing natural gas generators with thermal energy storage (TES) technologies. Thermal energy generators—particularly clean firm thermal generation via nuclear energy —carry the potential to effectively store thermal energy during times of low demand, then use this stored energy to ramp up generation during high-demand periods. For example, with high VRE penetration, during hours of high solar and/or wind generation, thermal energy can be stored while largely relying on the VRE sources to cover the electrical demand. When solar and/or wind are unavailable, the stored thermal energy can be released to i provide flexible generation and thus cover the electrical demand. Currently, much of this flexible, dispatchable energy comes from natural gas generators. One area of investigation is to determine whether carbon-free TES could replace these natural gas generators. The capability of TES to displace natural gas generators depends not only on economics but also the physical limitations of the TES units.

To accurately contrast the performance of natural gas generators versus TES, this work encompassed a literature review regarding current natural gas generator deployment, operation, and limitations in the U.S., deriving a baseline for benchmarking current natural gas generator models in HYBRID. These performance statistics were then contrasted with the expected behavior of the proposed TES technologies.

2 METHODS

This section summarizes the first example of autoloading data from HYBRID to HERON, then provides an overview and discussion of the methodology used in this study to evaluate the response times of energy storage technologies and natural gas generators.

2.1 FORCE Vertical Integration

HERON uses the Extensible Markup Language (XML) for its input file structure. The input XML file comprises three main parts (nodes): (1) the ‘Case’ node, which includes the general physics and economics information required to create a HERON workflow; (2) the ‘Components’ node, which includes the technical and economic information of each IES grid component, and (3) the ‘Data Generators’ node, in which data are processed. While all these nodes are created or modified by the user, all information contained in the ‘Components’ node can be imported from the output of the HYBRID simulations.

In this work, we automated the loading of economic data from the HYBRID text files to the HERON XML input file. Figure 1 shows an example of such data (previously manually transferred), illustrating some of the high-temperature steam electrolysis unit economic information imported from the HYBRID text files.[1]

2.1.1 Assumptions

Automation of the data transfer from HYBRID to HERON involved the following assumptions:

- The HYBRID text file data may be incomplete. In other words, the HERON input XML file may require more data before it can be run. Therefore, not only are data autoloaded from HYBRID to HERON, but default values are assigned to those variables that cannot be extracted from the HYBRID text files but are nonetheless required by HERON.

For example, the capital expenditures (CAPEX) cash flow type is not found in HYBRID, but its default value is known to be “one time.” Furthermore, warning messages (comments) are added to the HERON input XML file and terminal output to notify users of the assigned default values.

- The HYBRID text files may include information irrelevant to creating the HERON input file.

c

Figure 1. Manual information transfer between a HYBRID text file (left) and the HERON XML file (right).

- Units in the HYBRID file may differ from those in the HERON file. Thus, the data auto-transfer also involves transferring the comments, since the units are typically included as comments. As a result, users can review the units (comments) and make any necessary changes.
- The names of the variables in the HYBRID text files are not standardized, and users can change them. However, in HERON, the names of variables (in the form of nodes and their attributes) are unchangeable.
- A variable in a HYBRID text file may correspond to multiple variables in the HERON input XML file. For example, the “reference size” HYBRID variable (see Figure 1) corresponds to two different nodes in the HERON input XML file.

2.1.2 Data Autoloading Process

The process of autoloading data from HYBRID to HERON is represented in Figure 2. The data are transferred via a Python script, whose output is the autoloaded HERON input file (see Figure 2).

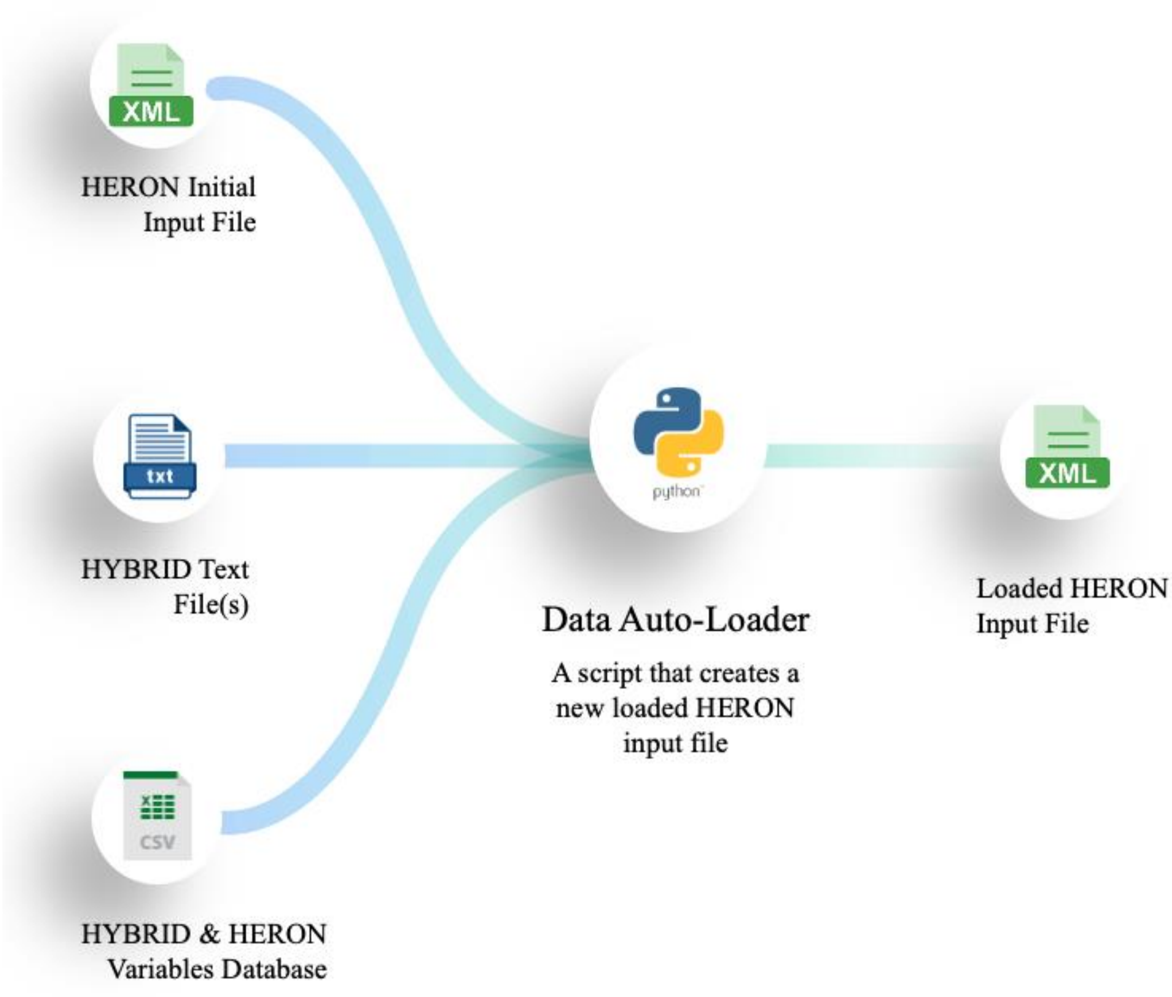

Figure 2. Process of autoloading data from HYBRID to HERON.

The structure of the initial HERON input XML file (seen on the left in Figure 2) resembles that of the typical HERON input XML file, except that the 'economics' sub-node found under any 'component' node does not include any economic data. Instead, users add the location of the HYBRID text file (in Figure 2) from which they wish to import the economic information. Further details on the structure of the HYBRID and HERON input files are explained in the User Manual for HYBRID-HERON Importer in APPENDIX A.

Another essential element of the HYBRID-to-HERON data autoloading process is the database (comma-separated values [CSV] file) that lists the HYBRID variables and their corresponding nodes in the HERON input XML file. Including the HYBRID and HERON variables in this database—instead of the Python autoloader script—is necessary because the names of the HYBRID variables can be changed, and additional variables may be considered in the future. Thus, if users plan to add/modify the HYBRID or HERON variables, they will not have to modify the Python code. Instead, simple changes will be made in the database file "HYBRID_ HERON_keywords.csv," which not only includes the names of the HYBRID/HERON variables but also more information on the relations between these variables (see the User Manual for HYBRID-HERON Importer in APPENDIX A). Table 1 lists the variables that have been considered thus far.

The Python autoloader script autoloads the data from HYBRID to HERON via the following steps:

- Reading the initial HERON input XML file and identifying the 'economics' node that must be autoloaded from HYBRID, under any 'component' node.
- Reading the HYBRID text file(s) and identifying the name of the variables, the values, and any corresponding comments.
  - Based on the existing HYBRID variables, additional ones not found in the HYBRID text files may be added, as they are variables required by HERON. This step is necessary to ensure that the HERON input XML file is complete, and because the HYBRID files do not always provide all the needed information.
    - Default temporary values are assigned to these additional variables, which were absent in the HYBRID files.
    - Warning messages inform users about the assigned default values that must be reviewed /modified by the user.
- Creating HERON nodes that correspond to the HYBRID variables, based on the HYBRID-HERON variable database.
- Loading the "economics" node of each component with the new HERON nodes.

An example of data transfer from HYBRID to HERON is presented in Section 3.1.

Table 1. HYBRID economic variables autoloaded from HYBRID to HERON.

Variable name	Definition
Activity	"Activity" indicates that this value will be taken from the dispatched activity of this component, and will serve as the main driver of this cash flow type.
Amortization_lifetime	The lifetime over which the cost of the assets is reduced.
capex	The CAPEX cash flow reference price fixed value.
capex_inflation	Determines how inflation affects the CAPEX cash flow every cycle.
capex_multi_target	Indicates whether this parameter (CAPEX cash flow) should be a target of the multiplication factor for net present value matching analyses.
capex_name	The name of this cash flow.

Variable name	Definition
capex_period	The period for a “repeating” cash flow, indicating whether the cash flow repeats every time step (hour) or every cycle (year).
capex_taxable	Determines whether the CAPEX cash flow is taxed every cycle.
capex_type	Type of CAPEX cash flow. The one-time type is suitable for CAPEX cash flows.
capex_variable	The name of the variable from inner RAVEN variables. This variable is the main driver for the CAPEX cash flow.[2]
Economies_of_scale	Determines the scaling factor for this cash flow.
FOM	The FOM cash flow reference price fixed value.
FOM_inflation	Determines how inflation affects the FOM cash flow every cycle.
FOM_multi_target	Indicates whether this parameter (FOM cash flow) should be a target of the multiplication factor for net present value matching analyses.
FOM_name	The name of this cash flow.
FOM_period	The period for a “repeating” cash flow, indicating whether the cash flow repeats every time step (hour) or every cycle (year).
FOM_taxable	Determines whether the FOM cash flow is taxed every cycle.
FOM_type	The type of FOM cash flow. The repeating type is suitable for repeating costs such as operations and maintenance (fixed or variable).
FOM_variable	The name of the variable from inner RAVEN variables. This variable is the main driver for the FOM cash flow.[2]
Lifetime	The number of cycles (often years) over which this unit is expected to operate prior to replacement.
reference_size	The reference driver determines the number of units that were sold at the reference price.
VOM	The VOM cash flow reference price fixed value.
VOM_inflation	Determines how inflation affects the VOM cash flow every cycle.
VOM_multi_target	Indicates whether this parameter (VOM cash flow) should be a target of the multiplication factor for net present value matching analyses.
VOM_name	The name of this cash flow.
VOM_period	The period for a repeating cash flow, indicating whether the cash flow repeats every time step (hour) or every cycle (year).
VOM_taxable	Determines whether the VOM cash flow is taxed every cycle.
VOM_type	The type of the VOM cash flow. The repeating type is suitable for repeating costs such as operations and maintenance (fixed or variable).

2.2 Contrasting Natural Gas Generators and Energy Storage Ramp Rates

Designing appropriate IESs requires a better understanding of their transient behaviors. The current work aims to provide such knowledge by analyzing a few selected studies—namely, on concrete energy storage, compressed air storage, and sensible heat storage—then comparing these energy storage technologies' transient response times to that of natural gas generators. The ramping rates of the selected energy storage cases within HYBRID are verified by looking for differences or discrepancies between the models and the experimental or field data available in the literature. The response times of these technologies were then compared to that of natural gas generators, as derived from a database compiled by the U.S. Energy Information Administration (EIA).[3] This database is part of Form EIA-860, a survey released on September 9, 2021, that collected generator-level specific information on existing/planned generators and associated environmental equipment at electric power plants.

2.3 Validating Assumptions about Models in HYBRID *(Specifically Ramping Limitations for Natural Gas, Thermal Energy Storage)*

When coupling energy storage to a nuclear power plant (NPP), a plant can divert its electrical output (e.g., compressed air storage, in the case of electric energy storage) or large quantities of steam over to storage (in the case of TES) when demand is low and electricity prices are even lower, without requiring major modifications to the turbine hall. In this way, the reactor always operates at full capacity. During periods of higher demand/prices, the stored energy is sent back to the power cycle, or to a secondary power cycle dedicated to the energy storage system. This type of strategy boosts the plant power output. Implementing storage integration into NPPs increases the "baseload" capacity and enhances their capability to rapidly and dynamically ramp down their power levels. This work evaluates the ramping capabilities and response times of three energy storage models developed in HYBRID, compares them against the data found in the literature, and contrasts them with the response time of natural gas generators. The maximum charging power (i.e., charging ramp rate) results from HYBRID are reported for each technology, and the geometry and assumptions for each model are discussed.

While the additional response time needed for the turbine to respond and generate the additional capacity is not yet modeled by the current HYBRID models, the additional response time needed for this step is assumed negligible when the thermal storage coupling follows an integrated storage system design. With this coupling option, though the energy storage system and its components are still treated as a standalone subsystem, the steam is sent from thermal storage to the NPP's main turbine hall. This main turbine always operates at the reactor's minimum baseload conditions. This enables a fast response to changing electricity demand whenever stored heat is returned to the main turbine hall, as opposed to a standalone turbine that begins operation from a cold start, as in the case of a natural gas "peaker" plant. Hence, when compared to natural gas peaker plants, the additional response time to ramp the turbine is assumed negligible for thermal storage technologies when coupled with an NPP as an IES.

3 RESULTS

3.1 FORCE Vertical Integration

3.1.1 Demonstration

This section demonstrates an example of autoloading components' economic information from the HYBRID text file(s) to the HERON input XML file. Figure 3 shows the text files containing the components' economic information in HYBRID. The components are categorized as either "source" and "sink." A "source" component produces one or more resources by consuming other resources. Such components may be sources of nuclear energy, solar energy, or wind, or may be natural gas energy generators. "Sink" components exclusively demand a specific resource. The sink can be the electricity market or hydrogen market. The HYBRID text files in Figure 3 include economic variables and their values, along with some comments. Definitions of the variables given in the Figure 3 text files are listed in Table 1.

```
[source]
Lifetime = 20 #years

  [source.Economics]
  capex = 545263737 #Reference is INL/EXT-19-55395
  FOM = 70752705
  VOM = 100 # Just a placeholder to make sure it passes through
  reference_size = 7.4 #kg/s of Hydrogen
  Economies_of_scale = 0.955
  Amortization_lifetime= 15 #years
  Activity = a
```

```
[sink]
Lifetime = 30 #years

  [sink.Economics]
  VOM = 0 # Just a placeholder to make sure it passes through
  Activity = a
```

Figure 3. HYBRID text files of two component types: source and sink.

Prior to the data transfer from HYBRID to HERON, the user specifies the location of the HYBRID files that contain the needed information on the given component. Figure 4 shows the 'economics' sub-node belonging to each component type (i.e., source and sink) prior to transferring the data from HYBRID. The only information included in the <economics> sub-node is the location of the HYBRID files.

```
<economics src="Costs/source/source.toml"></economics>
```

```
<economics src="Costs/sink/sink.toml"></economics>
```

Figure 4. The 'economics' sub-nodes (in the initial HERON input file) of two components (source and sink) prior to autoloading the data from HYBRID.

When the economic information is loaded (as explained in Section 2.1), the 'economics' sub-node is loaded with information, comments transferred from the HYBRID text files (e.g., units), and warnings for the user to consider. Figure 5, Figure 6, and Figure 7 show the "source" economic data autoloaded to the HERON input file, while Figure 8 shows the "sink" autoloaded data.

Note that all the comments in the HYBRID files are transferred to the corresponding nodes in the HERON input XML file. Some nodes and their attributes were not provided by HYBRID (e.g., inflation or cash flow type), so default values were assigned: inflation was assumed to be "none" and cash flow type was assumed to be "one-time" (for the CAPEX cash flow) and "repeating" for the fixed operation and maintenance (FOM) and variable operation and maintenance (VOM) cash flows. Warnings (comments) were added to notify users of each variable not provided by HYBRID.

Note that the singe line of code under the 'economics' node prior to data transfer is replaced by around 80 lines (for the source component) or 20 lines (for the sink component) in the autoloaded HERON input XML file. This shows the benefit of autoloading data rather than entering them manually, which would have been much more time consuming and error prone, especially if the user had to frequently update the HERON input file.

3.2 Natural Gas and Energy Storage Ramp Rate Results and Verification

This section summarizes the ramp rates of natural gas generators, then provides an overview and discussion of the response time results of various TES technologies.

3.2.1 Natural Gas

To determine the average response time of current natural gas generators, a database (generated via 2020 Form EIA-860) of the existing 23,419 natural gas generators in the U.S. was analyzed. The natural-gas-fired combined-cycle units covered in this survey had a combined electricity generation capacity of 551 GW. Of that capacity, only 5.6% came from fast generators (response time of under 10 minutes), as shown in Figure 9 and Table 2. Natural-gas-fired generators with longer response times were more common. The percentage of generation capacity stemming from natural gas generators that required response times of 1–12 hours to reach full operations was 56.27%, whereas 26.27% came from units with a response time of 10 minutes to an hour.

```xml
<economics>
  <!--This 'economics' subnode is created using information from the HYBRID simulations-->
  <lifetime>
    20
    <!--years-->
  </lifetime>
  <CashFlow inflation="none" mult_target="FALSE" name="capex" taxable="TRUE" type="one-time">
    <!--Warning: The value of 'capex_inflation' is not provided by HYBRID. A default value is
    assigned instead. It needs to be reviewed or replaced-->
    <!--Warning: The value of 'capex_multi_target' is not provided by HYBRID. A default value
    is assigned instead. It needs to be reviewed or replaced-->
    <!--Warning: The value of 'capex_name' is not provided by HYBRID. A default value is
    assigned instead. It needs to be reviewed or replaced-->
    <!--Warning: The value of 'capex_taxable' is not provided by HYBRID. A default value is
    assigned instead. It needs to be reviewed or replaced-->
    <!--Warning: The value of 'capex_type' is not provided by HYBRID. A default value is
    assigned instead. It needs to be reviewed or replaced-->
    <depreciate>
      15
      <!--years-->
    </depreciate>
    <reference_price>
      <!--Reference is INL/EXT-19-55395-->
      <fixed_value>545263737</fixed_value>
    </reference_price>
    <reference_driver>
      <!--kg/s of Hydrogen-->
      <fixed_value>7.4</fixed_value>
    </reference_driver>
    <scaling_factor_x>
      <fixed_value>0.955</fixed_value>
    </scaling_factor_x>
    <driver>
      <!--Warning: The value of 'capex_variable' is not provided by HYBRID. A default value
      is assigned instead. It needs to be reviewed or replaced-->
      <variable>source_capacity</variable>
    </driver>
  </CashFlow>
```

Figure 5. The ‘economics’ sub-node (CAPEX cash flow information), in the final HERON input file, of the source component after autoloading the data from HYBRID.

```xml
<CashFlow inflation="none" mult_target="FALSE" name="FOM" taxable="TRUE" type="repeating">
  <!--Warning: The value of 'FOM_inflation' is not provided by HYBRID. A default value is
  assigned instead. It needs to be reviewed or replaced-->
  <!--Warning: The value of 'FOM_multi_target' is not provided by HYBRID. A default value
  is assigned instead. It needs to be reviewed or replaced-->
  <!--Warning: The value of 'FOM_name' is not provided by HYBRID. A default value is
  assigned instead. It needs to be reviewed or replaced-->
  <!--Warning: The value of 'FOM_taxable' is not provided by HYBRID. A default value is
  assigned instead. It needs to be reviewed or replaced-->
  <!--Warning: The value of 'FOM_type' is not provided by HYBRID. A default value is
  assigned instead. It needs to be reviewed or replaced-->
  <depreciate>
    15
    <!--years-->
  </depreciate>
  <reference_price>
    <fixed_value>70752705</fixed_value>
  </reference_price>
  <reference_driver>
    <!--kg/s of Hydrogen-->
    <fixed_value>7.4</fixed_value>
  </reference_driver>
  <scaling_factor_x>
    <fixed_value>0.955</fixed_value>
  </scaling_factor_x>
  <driver>
    <!--Warning: The value of 'FOM_variable' is not provided by HYBRID. A default value is
    assigned instead. It needs to be reviewed or replaced-->
    <variable>source_capacity</variable>
  </driver>
</CashFlow>
```

Figure 6. The ‘economics’ sub-node (FOM cash flow information), in the final HERON input file, of the source component after autoloading the data from HYBRID.

3.2.2 Energy Storage Technologies

To determine the average response time of energy storage technologies, two verification approaches were considered: (1) summarizing the experimental or field data available in the literature, and (2) verifying the ramp rates of the selected energy storage cases that exist in the HYBRID models.

Table 4 lists various energy storage technologies and their response times, based on the available data in the literature. It is apparent that the response times of most energy storage technologies range from a few seconds to a couple of minutes on the low end, and still come in at under an hour on the high end. Figure 10 visually illustrates the response times of these technologies.

```xml
  </CashFlow>
  <CashFlow inflation="none" mult_target="FALSE" name="VOM" taxable="TRUE" type="repeating">
    <!--Warning: The value of 'VOM_inflation' is not provided by HYBRID. A default value is
    assigned instead. It needs to be reviewed or replaced-->
    <!--Warning: The value of 'VOM_multi_target' is not provided by HYBRID. A default value
    is assigned instead. It needs to be reviewed or replaced-->
    <!--Warning: The value of 'VOM_name' is not provided by HYBRID. A default value is
    assigned instead. It needs to be reviewed or replaced-->
    <!--Warning: The value of 'VOM_taxable' is not provided by HYBRID. A default value is
    assigned instead. It needs to be reviewed or replaced-->
    <!--Warning: The value of 'VOM_type' is not provided by HYBRID. A default value is
    assigned instead. It needs to be reviewed or replaced-->
    <depreciate>
      15
      <!--years-->
    </depreciate>
    <reference_price>
      <!-- Just a placeholder to make sure it passes through-->
      <fixed_value>100</fixed_value>
    </reference_price>
    <reference_driver>
      <!--kg/s of Hydrogen-->
      <fixed_value>7.4</fixed_value>
    </reference_driver>
    <driver>
      <activity>a</activity>
    </driver>
  </CashFlow>
</economics>
```

Figure 7. The ‘economics’ sub-node (VOM cash flow information), in the final HERON input file, of the source component after autoloading the data from HYBRID.

The following sections evaluate the response times of the three selected energy storage models already developed in HYBRID.

3.2.2.1 Compressed Air Energy Storage

Compressed air energy storage (CAES) is a technology for storing potential energy by compressing air during times when electricity production exceeds the demand. This compressed air can be stored in large reservoirs and be used to generate additional power via a gas turbine during times of peak electricity demand. The current CAES system model in HYBRID is divided into two submodules: one that models the charging and storage phases, and one that models the discharging phase. The models are separated based on the underlying limitations of the turbomachinery components, as later discussed.

```xml
<economics>
  <!--This 'economics' subnode is created using information from the HYBRID simulations-->
  <lifetime>
    30
    <!--years-->
  </lifetime>
  <CashFlow inflation="none" mult_target="FALSE" name="VOM" taxable="TRUE" type="repeating">
    <!--Warning: The value of 'VOM_inflation' is not provided by HYBRID. A default value is
    assigned instead. It needs to be reviewed or replaced-->
    <!--Warning: The value of 'VOM_multi_target' is not provided by HYBRID. A default value
    is assigned instead. It needs to be reviewed or replaced-->
    <!--Warning: The value of 'VOM_name' is not provided by HYBRID. A default value is
    assigned instead. It needs to be reviewed or replaced-->
    <!--Warning: The value of 'VOM_taxable' is not provided by HYBRID. A default value is
    assigned instead. It needs to be reviewed or replaced-->
    <!--Warning: The value of 'VOM_type' is not provided by HYBRID. A default value is
    assigned instead. It needs to be reviewed or replaced-->
    <reference_price>
      <!-- Just a placeholder to make sure it passes through-->
      <fixed_value>0</fixed_value>
    </reference_price>
    <driver>
      <activity>a</activity>
    </driver>
  </CashFlow>
</economics>
```

Figure 8. The ‘economics’ sub-node, in the final HERON input file, of the sink component after autoloading the data from HYBRID.

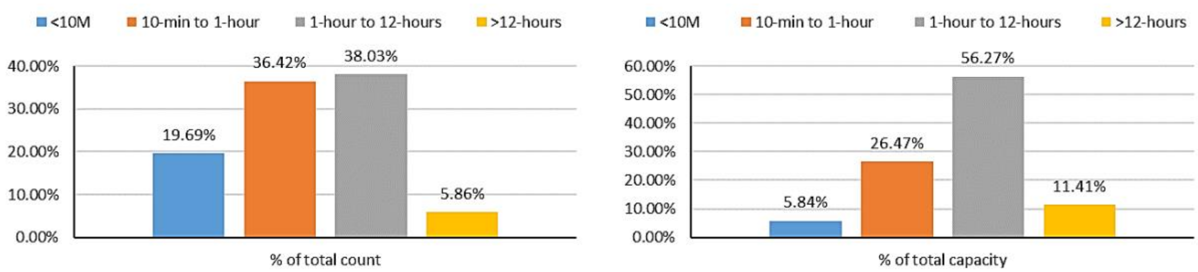

Figure 9. U.S. natural gas generation count (left) and capacity (right) by response time (2020).

Table 2. U.S. natural gas generation count (left) and capacity (right) by response time (2020).

Response time	Count	Count %	Capacity %	Generation Capacity (MW)
<10 min	1079	19.69%	5.84%	32241.6
10 min to 1 hour	2315	36.42%	26.47%	146036
1 to 12 hours	2334	38.03%	56.27%	310437.7
>12 hours	343	5.86%	11.41%	62951.4
Grand Total	6071	100.00%	100.00%	551666.7

Most of the natural-gas-fired capacity added in recent decades uses combined-cycle technology, which produces even slower response times, despite the technological improvements that have led to improved efficiency.[4] Table 3 shows the results of analyzing the EIA-860 U.S. natural gas generation database, listing the average response time of each technology type.

Table 3. 2020 U.S. natural gas generation count, capacity, and response time by technology type.

Generator Technology	Count	Generation (nameplate) Capacity (MW)	Generation Capacity %	Average Response Time in Minutes
Natural Gas Combined Cycle	1952	310757.9	56.33%	315.1
Natural Gas Combustion Turbine	2237	153687.2	27.86%	62.5
Natural Gas Internal Combustion	1144	5353.3	0.97%	46.4
Natural Gas Steam Turbine	580	81514.5	14.78%	477.7
Natural Gas Compressed Air Storage	1	110.0	0.02%	30.0
Other Natural Gas	161	257.8	0.05%	478.8

Table 4. Response times of energy storage technologies, based on available data in the literature.

Storage Technology		Response time	Typical charge/ discharge time	Ref
Mechanical	Pumped-storage hydropower	minutes	hours	5,6
	Compressed air energy storage	sec – mins	hr – day	6,7
	Flywheels	seconds	minutes	5,8
Electrical	Supercapacitors	millisecs	millisecs – hrs	7,8
	Superconducting magnetic energy storage	millisecs	millisecs – sec	7,8
Electrochemical batteries	Lithium-ion	millisecs	min – hrs	9
	Lead-acid	millisecs	sec – hrs	10
Chemical	Hydrogen fuel cell	sec – 24 hrs	min – hrs	11,12
Thermal – Sensible heat	Two-tank molten salts or thermal oils	1–10 min	hrs	15
	Thermocline molten salts or thermal oil	~10 min	hrs	–
	Underground	10 min – 1 hr	–	–
	Hot and cold tanks	secs – 1 hr	mins – hrs	13
	Solid media (concrete)	minutes	hrs to 1 day	14

Storage Technology		Response time	Typical charge/ discharge time	Ref
Thermal – Latent heat	Molten salts as PCMs or latent heat	~10 min	hrs	6
Thermal – Other	Thermochemical	minutes – 1 hr	1 – 24 hrs	7
	Steam accumulators	sec – 1 min	hrs	5,6

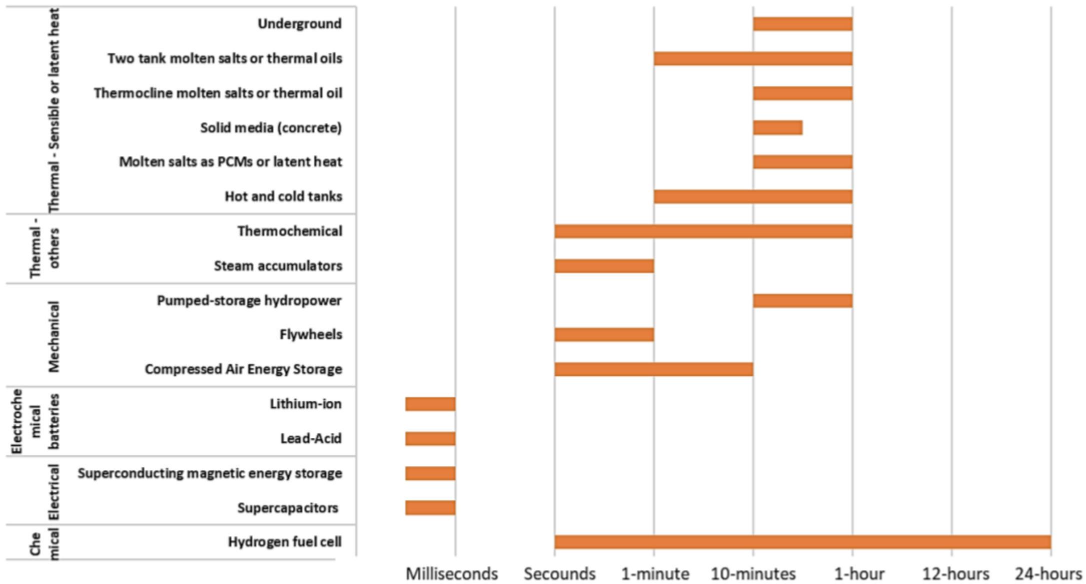

Figure 10. Visual illustration of energy storage technology response times, based on the available data in the literature.

Figure 11 shows the charging cycle and control mechanism of the CAES model. During the charging phase, a compressor compresses air to below atmospheric pressure and fills the storage cavern. The charging power of the compressor depends on the power input from the grid, which is currently accessed as tabulated data. Next, a Proportional Integral (PI) controller, which reduces the rate of error for the compressor operating power and grid input, controls the rotational speed of the compressor. Once the cavern reaches a predetermined pressure, the cavern valve is closed and an atmospheric sink valve opened. This prevents the compressor from dead-heading, as conditions in the current compressor model cannot be slowed down to zero-to-low flow. This limitation is primarily due to the underlying compressor maps that dictate compressor performance. The current compressor map forces the compressor to operate at 95–105% of its nominal speed. Better data are needed to enable the compressor to operate beyond these conditions.

Once the charging cycle has ended and the cavern valve has been closed, the cavern enters its storage phase. During storage, the air within the cavern exchanges heat at its boundary and cools down. This also leads to a drop in storage pressure. The final air pressure and temperature values are then used as input parameters for the discharge phase.

The discharging model was developed in similar fashion to the charging-plus-storage model. Figure 12 shows the discharging model and appropriate control mechanism of the CAES system. During the discharging cycle, the cavern depressurizes, providing air to a turbine that restores it to atmospheric conditions and produces electricity. The discharge rate of the cavern is controlled by a turbine valve, which takes power from the grid as input and controls the flow rate to meet the power demand. Once the cavern reaches its minimum operating pressure, the cavern valve is then closed, stopping the air flow. A secondary mass flow rate source then provides air flow to the turbine. This prevents the turbine from dead-heading, as it also operates on performance maps that limit its operating range. It is evident that the turbomachinery components' operating limits do not allow them to start or end at low-to-zero flow, which is why the charging/discharging cycles are separated. During the charging cycle, the turbine would experience low flow conditions, whereas during the discharging cycle, such would be the case with the compressor. As neither component can operate under such conditions, the cycles had to be separated.

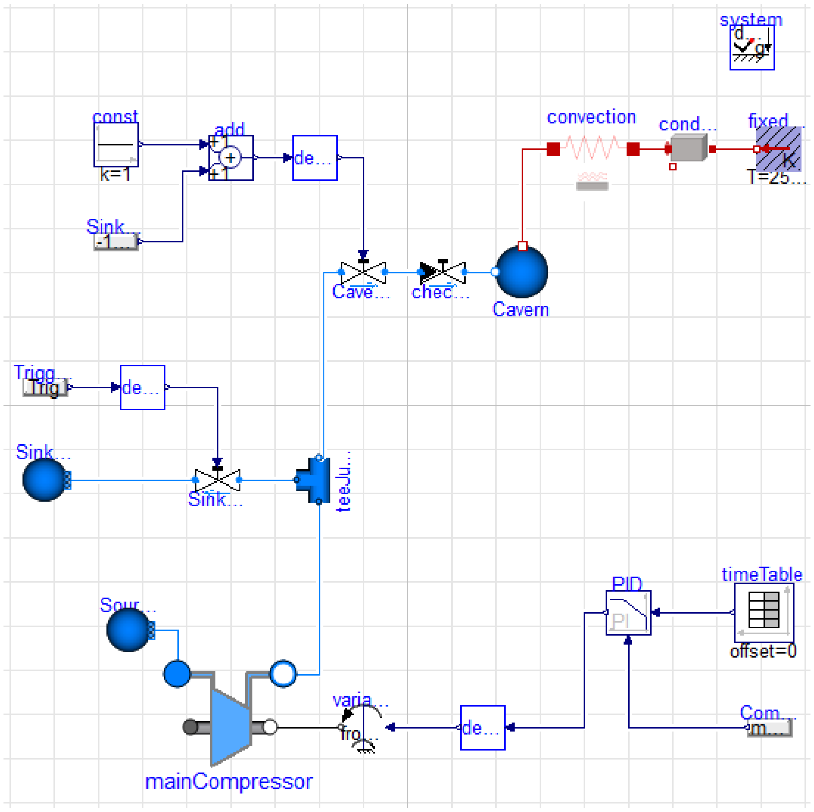

Figure 11. Charging cycle of the CAES model.

It should be noted that the tabulated performance data for the compressor and turbine are based on real components and thus account for the mechanical inertia such components would experience when their power is ramped up or down. The response time result of ramping the turbine power to meet the grid demand during the discharging cycle is shown in Figure 13.

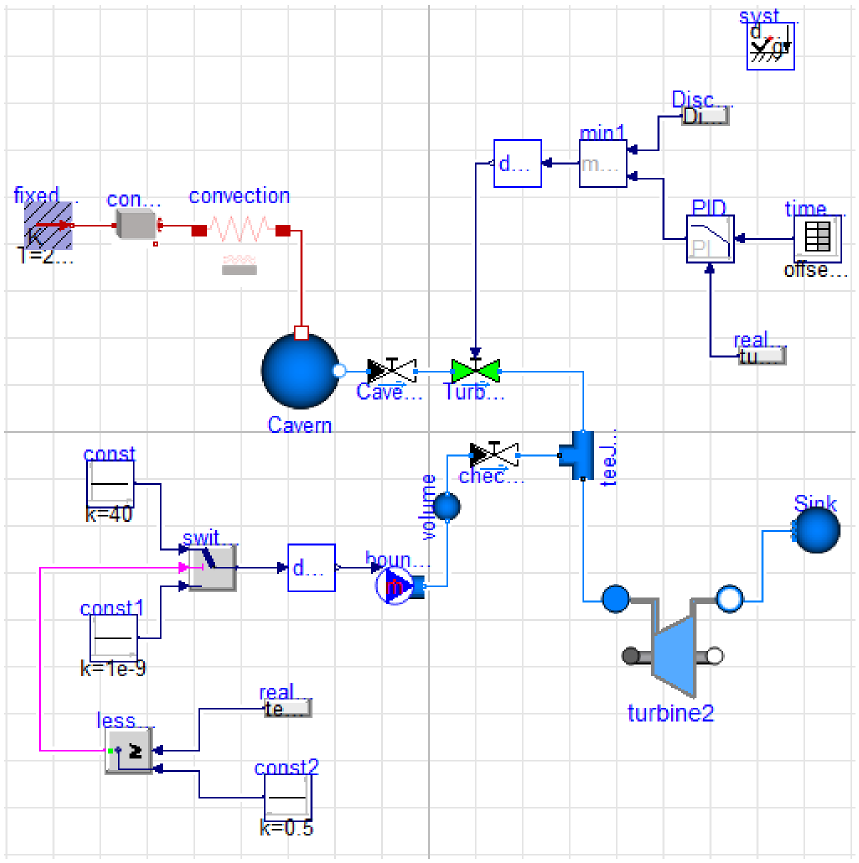

Figure 12. Discharging cycle of the CAES model.

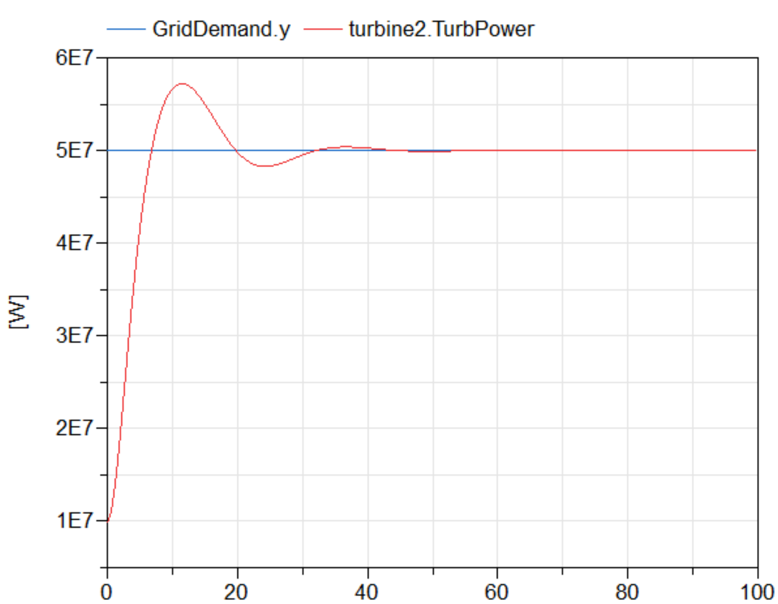

Figure 13. CAES ramping of turbine power to meet the grid demand during the discharging cycle.

After starting out at 10 MW, the turbine ramps up to 50 MW (based on the grid demand) within 6.8 seconds. However, it overshoots the power demand, due to the current control mechanism, then takes about 53 seconds to stabilize.

The current focus of CAES system developers is to expand the operating range of these turbomachinery components to encompass wider variations in flow conditions. Once this is achieved, the charging and discharging cycles will be combined into a single model.

3.2.2.2 Sensible Heat Thermal Energy Storage

The sensible heat TES (SHTES) technology covered in this section is based on a two-tank sensible heat storage system that exists in the HYBRID repository. Conceptually, the necessary components for the two-tank loop design are two tanks (a hot and a cold) that exchange fluids at controllable rates. Thus, the system operates by using pumps to pull flued from each tank and direct the flow through a control valve. After passing through the control valve, the fluid flows through heat exchangers (either for charging or discharging) before entering the other tank.

To demonstrate the response time of SHTES, a test case for the two-tank Sensible Heat Storage (SHS) system was created, producing steam at 5 bar. The demand periodically reached as high as 2 kg/s. Figure 14 shows the SHTES model, and control mechanism. When the hot tank level drops below 3 m, the test system charges it back up to 13 m via a hysteresis controller. The hot tank temperature is controlled at a constant value. The full steam production process is as follows: (1) fluid is constantly cycled through the discharging heat exchanger at 25 kg/s; (2) the steam valve at the exit of the boiler drum is designed to open whenever the pressure in the drum exceeds 5 bar; and to produce steam, (3) the fluid exiting the bottom of the boiler drum must travel through the discharge heat exchanger, undergo heating, then return. Thus, some minor delays are expected to occur during operation.

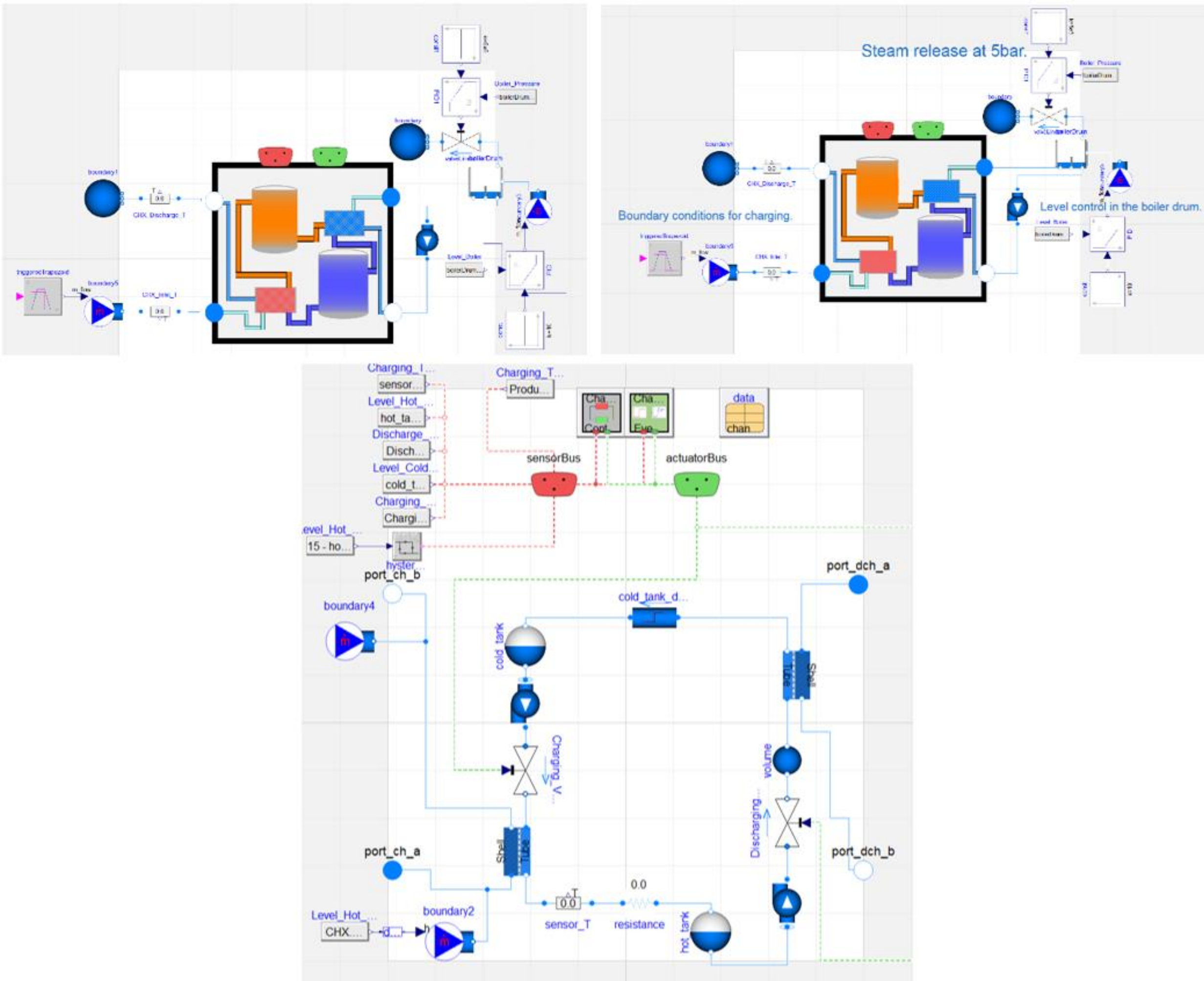

Figure 14. Diagram of the sensible heat system model in HYBRID.

The system has been tested as a standalone system. As mentioned above, the testing method was to produce 2 kg/s of steam at 5 bar (70 psia) for ~2.5 hours out of every 5. Charging then occurred for long enough to replenish the hot tank fluid level. Figure 15 shows the tank levels. Frequent decreases in the hot tank level and the corresponding rises in the cold tank level occur as steam is produced from the boiler unit. The charging and discharging power rates (i.e., ~9.2 and 4.2 MW_{th}, respectively) are seen in Figure 16.

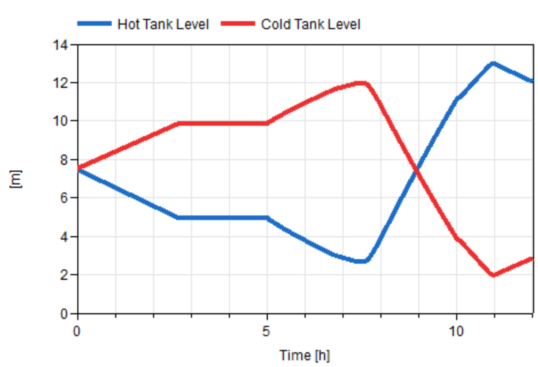

Figure 15. Hot and cold tank levels.

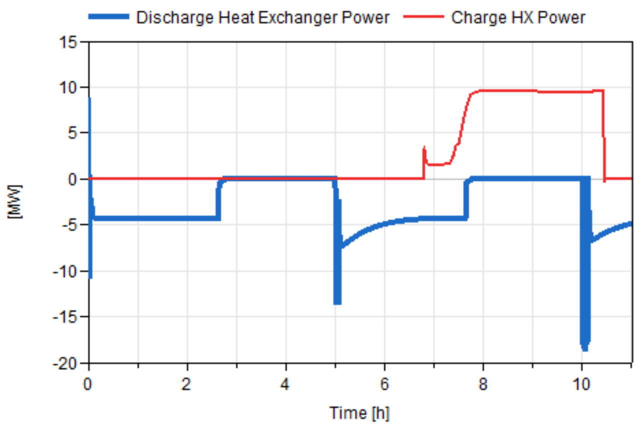

Figure 16. Discharge and charge power as measured within the heat exchangers.

Figure 17 compares the discharge mass flow rate (steam production) pattern against the steam demand. The response time can be acquired from these results by looking at the time it takes for the steam production to match the demand.

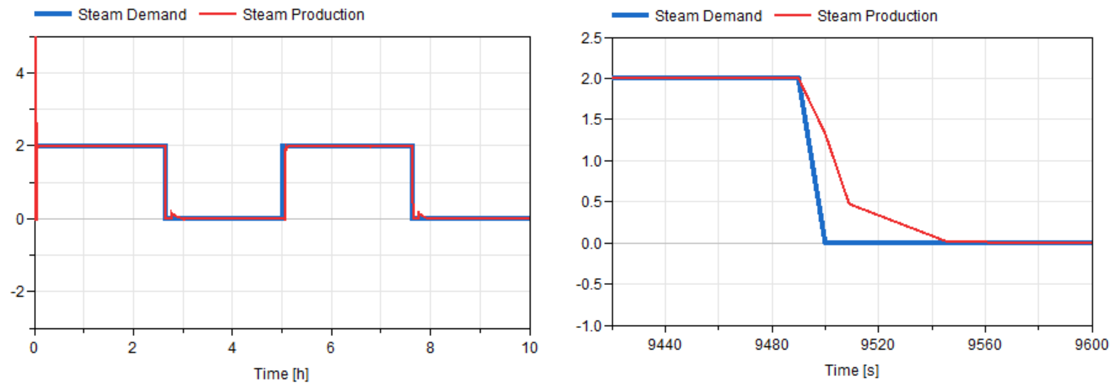

Figure 17. Discharge mass flow and normalized steam flow rate during a discharge cycle.

Overall, the sensible two-tank system is capable of enduring many charging, discharging, and standby cycles. Future improvements may be made to increase the speed of the model; however, based on the setup above, the ramp rate was determined to be well under 2 minutes.

In future work, the two-tank SHS system developers plan to further test the model in regard to additional applications. The HYBRID repository already contains multiple reactor models to integrate the system with. Future reactor models may also employ the SHS as an integral part of the design. This will require additional control system construction and energy application modeling.

3.2.2.3 Concrete thermal energy storage

The concrete TES (CTES) technology covered in this section represents a simple, low-cost sensible heat storage technology in which a heat transfer fluid is transported through tubes embedded in a concrete block that serves as the energy storage medium. Figure 18 shows a schematic of Storworks Power's individual storage element, as well as the complete module, known as the BolderBloc™ modular TES system.

Figure 18. Storworks Power's CTES BolderBloc^{TM} module.[16]

The CTES in the HYBRID repository contains three subsystems: heat transfer fluid (water/steam), piping, and concrete —all of which interact with each other during charting and discharging. The overall CTES system behavior is scaled by calculating the behavior of an average pipe. To demonstrate the CTES response time, a test case was created using the charging and discharging conditions listed in Table 5. This setup was based on a dual-pipe configuration that included separate pipes for both charging and discharging, with a corresponding mass of concrete between the two. The system was sized to deliver 5 MW_{th} during the discharging cycle. The total length of the concrete was 50 m, the thickness (spacing between the pipes) was 0.3 m, the inner diameter was 0.07 m, the outer diameter was 0.079 m, and the total number of pipes was 250. The total pipe length was 150 m. The discharge mass flow rate was based on power-controlled design criteria, such that the discharge power was maintained at 5 MW_{th}.

Table 5. Simulation parameters for CTES.

Variable	Value	Variable	Value
Charging power	Mass controlled	Discharge power	5 MW_{th}
Charging mass flow rate	13 kg/s	Discharging mass flow rate	Power controlled (5 MW_{th})
Charging pressure	21.3 bar	Discharging pressure	2.5 bar
Charge cycle time	7.8 hours	Discharging cycle time	7.8 hours
Total charging mass	42,120 kg	Total discharging mass	42,120 kg

Figure 19 shows the testing model for the CTES in HYBRID. Valves are periodically opened and closed to allow for three modes of operation: charging, discharging, and standby. Standby mode occurs when both valves are closed and there is no mass flow through the CTES. Charging occurs when the charging valve is opened, and discharging occurs when the discharging valve is opened.

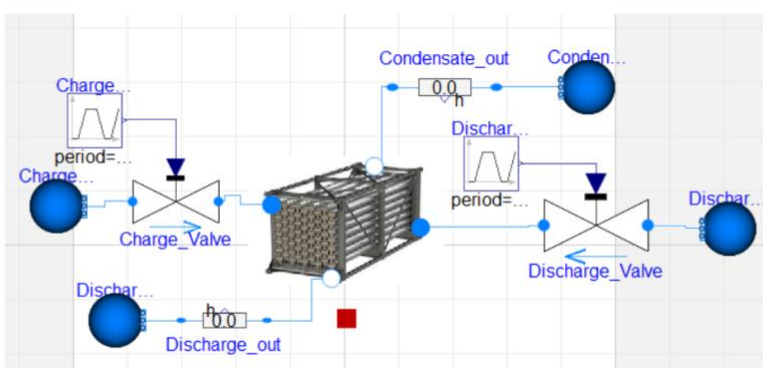

Figure 19. Concrete model testing that allows for charging and discharging operations within HYBRID.

Figure 20 shows the mass flow rate profile used for each test (bottom curve). A brief standby mode was inserted between the charging and discharging sessions. During the discharge curve, the mass flow rate is the power controller and thus is adjusted to maintain a discharge energy of 5 MWe. The top curve in Figure 20 shows the CTES content throughout the daily cycle, and this content is reset to 0 before the charging and discharging cycles. The energy content is measured by the heat being transferred in and out of the concrete surface. During the charting cycle, the power level is initially (and briefly) very high because the concrete surface is cold from the previous discharging, and extreme quenching occurs as the heat transfer fluid is cooled by the concrete. The initially higher charge rate is adjusted by lowering the mass flow rate during the first few minutes of the charge cycle, as reflected in the bottom curve. In the middle curve, the steam production (discharge power) is plotted against the power demand (5 MWe).

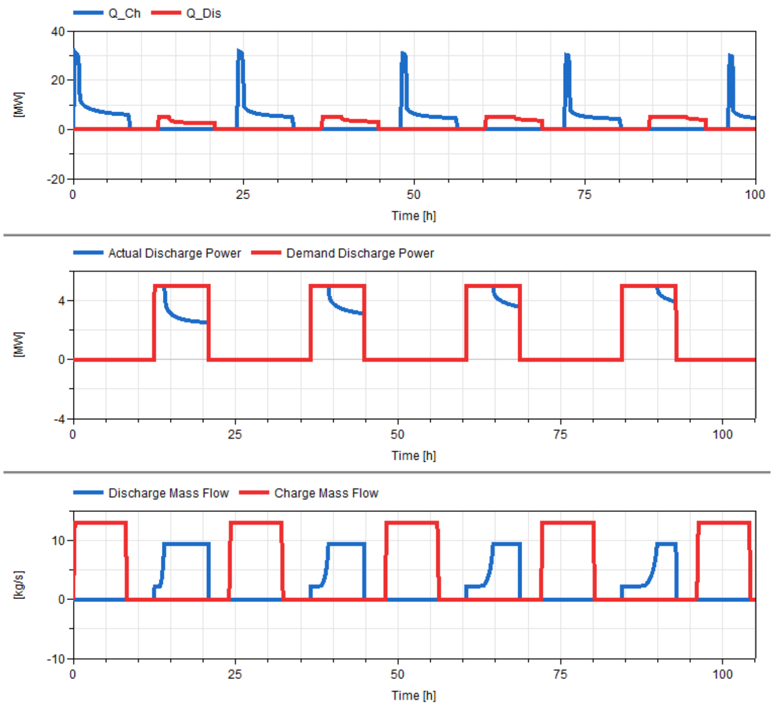

Figure 20. CTES testing model results. Top: Storage energy content during the charging and discharging cycle. Middle: Actual discharge power versus the 5 MW_{th} demand. Bottom: Charging and discharging mass flow rates during the test case.

By zooming in on one of the discharge cycles shown in Figure 20, the response time can be determined. Figure 21 shows that the CTES ramps up to 5 MW_{th} (based on the grid demand) within 90 seconds.

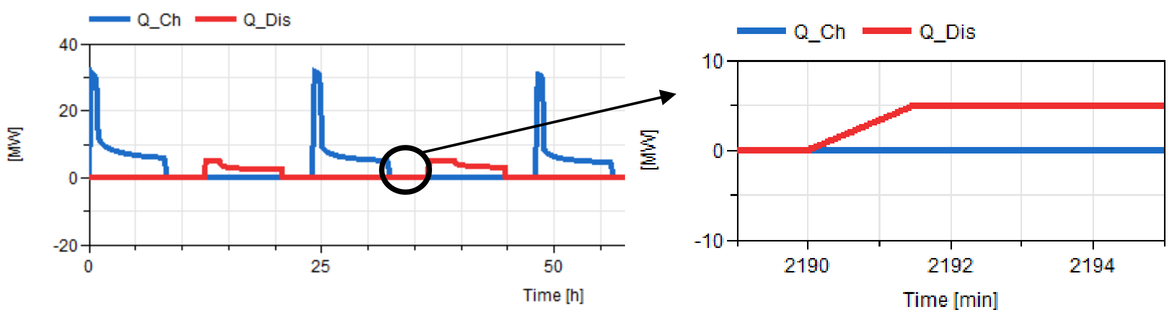

Figure 21. CTES response time during the discharging cycle.

4 CONCLUSIONS

4.1 FORCE Vertical Integration

FORCE is essential for modeling various IES configurations and providing an interface for accessing several code repositories, with each code answering a portion of the problem. This work is the first step in realizing automated data exchange between IES software tools. We have demonstrated an example of autoloading energy grid components' economic data from HYBRID to HERON. We showed that not only are the data autoloaded from HYBRID to HERON, but default values are also assigned to those variables whose values cannot be extracted from the HYBRID text values but are nonetheless required by HERON. The data transfer includes any user comments, in addition to the economic variables and their values. Since the names of the HYBRID variables are not standardized, users are provided with a separate database (CSV file) for the HYBRID variables' names where the variables' names can be modified, or new variables are incorporated. Automating the data transfer reduces the potential for error and is much less time consuming.

4.2 Benchmarking Methodology, Results, and Energy Storage Competitive Viability as Ramper

This report compared the response times of current natural gas generators in the U.S. with those of energy storage technology. It presented details on the ongoing progress and current system response times of three selected energy storage systems found in HYBRID. These system's ramping rates were derived from consistent values captured from the current HYBRID modes, as well as from the available data in the literature. The response times of the natural gas generators were derived from a database obtained from a EIA survey released on September 9, 2021, that summarized generator-level specific information on 23,419 natural gas generators.

Natural gas combined-cycle systems, which involve both a steam and a combustion turbine, account for more capacity than any other generating technology in the U.S. Most such systems require 1–12 hours to reach full operations, though some can start up within an hour, and only 5.6% of their combined capacity comes from fast response generators (<10 minutes). IES systems coupled with nuclear reactors present a unique opportunity and offer significant response time advantages over natural gas generators.

The response times of energy storage system per the HYBRID models are in good agreement with the literature data, and are superior to the natural gas generator response times. The literature data show that most energy storage technologies can respond within a range of a few seconds to a couple of minutes. The HYBRID results showed a response time of 53 seconds for compressed air storage, 2 minutes for two-tank sensible heat storage, and 1.5 minutes for concrete energy storage. Natural gas generators require much longer response times, with a minority of their response times falling within a 1–12 hour range for 56.27% of the generators surveyed, and 10 minutes to an hour for 26.27% of the generators surveyed.

5 FUTURE WORK

This status update will lead to a list of improvements to be made to the FORCE tool suite, and it supports research activities conducted by national laboratories, universities, and industry analysts. Vertical integration automation improves data pipelines within FORCE, increases usability, and reduces potential error sources for analysts. Benchmarking natural gas operations so as to contrast them with potential TES technologies opens the door to regional analyses focusing on decarbonization.

The CAES, SHS, and CTES models have achieved varying degrees of readiness for use in IES studies. Modelers believe that development is proceeding at a rate that will lead to the completion of all programmatic requirements. A high-level milestone report, related to model development within the integrated energy systems HYBRID repository, is due in summer 2022 and will provide a broad, clear picture of the overall status of recent model construction in the HYBRID repository. The response times of the energy storage technologies in this study are not expected to change and are already in good agreement with the experimental and field data found in the literature.

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APPENDIX A

User Manual for HYBRID-HERON Importer

Below is a new section that was added to the HERON user manual as a result of this project. The new chapter is titled "External Code Integration," and the full user manual can be found here: https://github.com/idaholab/HERON/tree/devel/doc/user_manual.

HERON can exchange data with other integrated energy system (IES) codes to conduct technical or economic analyses for various electricity market structures. More information on integrating HERON with other IES software is found here: https://ies.inl.gov/SitePages/FORCE.aspx.

Integration between HERON and other IES tools remains a work in progress. Currently, HERON can communicate with the following code (HYBRID).

A.1 HYBRID

The HYBRID repository contains a collection of models representing the physical dynamics of various IES and processes. HERON has the capability to load economic information on the grid system components automatically from HYBRID. More information on HYBRID can be found here: https://github.com/idaholab/HYBRID. An example demonstrating this capability can be found at:

```
/HERON/tests/integration_tests/mechanics/hybrid_load/
```

The Python script for autoloading the needed economic information from HYBRID to HERON is named hybrid2heron_economic.py, and can be found at:

```
/HERON/src/Hybrid2Heron/
```

The *hybrid2heron_economic.py* script takes one command-line argument"—namely, the path of the initial HERON input XML file (or pre-input file)—"? before loading any information from HYBRID. As an example, the terminal command looks like this:

```
python hybrid2heron_economic.py pre_heron_input.xml
```

A new HERON input XML file, heron_input.xml, is generated with all the sub-nodes under the **<economics>** node loaded from the HYBRID text files. The following subsections discuss additional details on the initial HERON input XML file, the generated (loaded) input XML file, and other files at /HERON/tests/integration_tests/mechanics/hybrid_load

A.1.1 Initial HERON Input XML File

The structure of the initial HERON XML file, pre_heron_input.xml, should resemble the typical HERON input XML file and must include:

- A <Components> node:
- At least one **<Component>** sub-node under the **<Components>** node, such as:

  <Component name="component_name"> </Component>

- An empty **<economics>** node under the **<Component>** node, with the path to the HYBRID text file that includes the needed information:

  <economics src="path/to/HYBRID/file"> </economics>

If the <economics> node is not empty, it will remain unaltered when creating the final HERON XML file, heron_input.xml.

An example of the initial HERON XML file, pre_heron_input.xml, is located at /HERON/tests/integration_tests/mechanics/hybrid_load/. The <Components> node at the pre_heron_input.xml looks like this:

```
<Components>
  <Component name="source">
    <!--Other component subnodes-->
    <economics src="Costs/source/source.toml"></economics> </Component>
</Components>
```

In this example, the economic information of the "source" component would be loaded from a text file whose path is /Costs/source/source.toml. Similarly, for any other component, the economic information can be provided from other text files.

A.1.2 HYBRID Text Files

The HYBRID text files are expected to have extensions such as .toml, .txt, or .rtf and are located at: /HERON/tests/integration_tests/mechanics/hybrid_load/Costs/ sink/sink.toml and /HERON/tests/integration_tests/mechanics/hybrid_ load/Costs/source/source.toml.

The HYBRID files do not have to be in the same folder with the pre_heron_input.xml as long as the value of the "src" parameter at the <economics> node is the path to the corresponding HYBRID text file. The HYBRID text file structure looks like this:

```
Lifetime = 30 # years
VOM = 0 # Just a placeholder to make sure it passes through
Activity = a
```

Each line in the HYBRID text file includes a variable name and corresponding value, plus a comment (if necessary). Any comments must start with #. The data should be appropriately autoloaded from the HYBRID text file to the HERON XML file, even if the text file includes additional irrelevant variables or additional comments at the top or bottom of the file.

A.1.3 Generated HERON Input XML File

The generated input file, heron_input.xml, includes:

- All information in the initial HERON input file, pre_heron_input.xml
- All relevant variables from the HYBRID text files
- Default values for additional variables found in neither the pre_heron_input.xml nor HYBRID text files, but that are required by HERON to ensure that the input XML file is complete, and that no required nodes or parameters are missing. The comments (warnings) inside the heron_input.xml inform users when the values of specific variables are not provided by HYBRID and default values are thus assigned instead. All users should review these comments/warnings.

A.1.4 HYBRID and HERON keywords

The HYBRID keywords or HYBRID variables identifiable by the hybrid2heron_economic.py code to create the corresponding HERON nodes are listed in the CSV file (i.e., HYBRID_ HERON_keywords.csv), located at /HERON/src/Hybrid2Heron. Understanding this CSV file is essential, especially if the user plans to add more HYBRID variables or modify existing ones. The CSV file, HYBRID_HERON_keywords.csv, includes the following columns:

- **HYBRID Keyword**: This column lists all the HYBRID variable names identifiable by the Python script, hybrid2heron_economic.py. The variables' names in the HYBRID text files must be a subset of the HYBRID variable names found in the HYBRID_HERON_ keywords.csv. Otherwise, users can change the variable names in either the HYBRID_ HERON_keywords.csv file or HYBRID text files.
- **Description**: The description or definition of each HYBRID variable.
- **HERON (Node or Parameter):** This column specifies whether the HYBRID variable corresponds to a HERON node or a node parameter in the HERON input XML file. *N* refers to a node, and *P* refers to a parameter.
- **HERON Node, HERON Sub-node, and HERON Sub-sub-node**: These three columns specify the location of the HERON node corresponding to a given HYBRID variable. For example, the HYBRID variable Activity corresponds the sub-sub-node **<activity>** under the **<driver>** sub-node under the **<CashFlow>** node:

```
<CashFlow inflation="none" mult_target="FALSE" name="VOM" taxable="TRUE"
     type="repeating">
       <driver>
              <activity>a</activity>
       </driver>
</CashFlow>
```

Also, the HYBRID variable "VOM_inflation" corresponds to a parameter ("P") or attribute called "inflation" at the node **<CashFlow>** under the **<economics>** node, as illustrated in the **<economics>** node (above).

- **Belong to same node**: This column is meant for determining the list of sub-nodes or parameters that belong to the same node. We consider four primary nodes under the **<economics>** node; namely, the component lifetime plus three types of cash flows: the capital expenditures (CAPEX) cash flow, the fixed operation and maintenance (FOM) cash flow, and the variable operation and maintenance (VOM) cash flow. These four primary nodes, listed under the **<economics>** node in the HERON input XML file, are as follows:

```
<economics>
   <lifetime>30</lifetime>
   <CashFlow inflation="none" mult_target="FALSE" name="capex" taxable="TRUE"
        type="one-time"></CashFlow>
   <CashFlow inflation="none" mult_target="FALSE" name="FOM" taxable="TRUE"
        type="repeating"></CashFlow>
   <CashFlow inflation="none" mult_target="FALSE" name="VOM" taxable="TRUE"
type="repeating"></CashFlow> </economics>
```

The numerical values under the "Belong to same node" column are either 0 or 1, or 2 or 3, corresponding to the nodes **<lifetime>**, **<CashFlow name="capex">**, **<CashFlow name="FOM">**, and **<CashFlow name="VOM">**, respectively.

For example, since the HYBRID variable "capex_inflation" corresponds to the parameter "inflation," under the node **<CashFlow name="capex">**, the corresponding numerical value under the "Belong to same node" is "1."

Similarly, the "Amortization_lifetime" HYBRID variable corresponds to the HERON sub-node **<depreciate>** under all three cash flow nodes; the corresponding numerical value under the "Belong to same node" is "1,2,3."

Note that we only consider three types of cash flows, but users can add cash flows to the HYBRID_HERON_keywords.csv file, if needed.

- **Required if HYBRID keyword?:** This column determines if the HYBRID variable must be included when building the HERON input XML file, even if this HYBRID variable is not provided by the HYBRID text files.

For example, the HYBRID variable "Activity" will be included if the "VOM" cash flow is present, since the node **<CashFlow name="VOM">** will be incomplete if the **<activity>** sub-node is missing. Therefore, for the HYBRID variable "Activity," the corresponding value under the "Required if HYBRID keyword?" column is VOM.

- **Default value for the required variable**: This column assigns a default value for any HYBRID variable whose value is not provided by the HYBRID text files, if this HYBRID variable is required (see the column "Required if HYBRID keyword?"). For example, the default value of the HYBRID variable "Activity," if required, is "electricity."