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Open Inertia Modelling (OpInMod) - An open source approach to model economic inertia dispatch in power systems

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Abstract

Open Inertia Modelling (OpInMod) is a modelling framework designed to create unit commitment and economic inertia dispatch optimisation problems. Present energy system modelling generators do not consider power system inertia in unit commitment and economic dispatch modelling to assess future energy system pathways. However, maintaining sufficient power system inertia in power systems is the foundation for power frequency controllability. The work at hand describes the functionality and approaches of open source tool OpInMod. The softwares universal design approach increases reuse potential. OpInMod is distributed with a set of examples to test and understand OpInMod

Keywords: Economic Inertia Dispatch Modelling, Energy System Modelling, Power System Inertia, Renewable Energy, Synthetic Inertia

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(1) Overview

Introduction

The integration of Renewable Energy Sources (RESs) is one of the main approaches to decarbonise energy systems and limit global warming. Therefore, fossil fuel fired power plants get replaced with RESs, to a large extend with Photovoltaics (PVs) and Wind Turbines (WTs) [1]. State of the art PVs and WTs are connected to the power system via grid frequency converters [2]. Therefore, grid operators and authorities have to review ancillary services like grid frequency control, more precisely controllability of low inertia power systems [1, 3]. System inertia refers to the inherent response of synchronously connected rotating masses in the event of a power imbalance [2]. The inherent response reduces the speed with which the grid frequency, the indicator for power balance, changes [4]. Additionally, exchanged kinetic energy between the rotating masses and the power system reduces the grid frequency nadir [4]. Replacing synchronous generators with inverter connected RES results in reducing overall system inertia [2]. Power systems characterised by low rotational inertia might ultimately results in a full system blackout in the even of a power imblance [2].

Energy system modelling is an important part of energy system analysis [5]. Its main purpose ranges from designing, planning and implementing energy systems [6] analysing topics like power system stability, grid planing, unit commitment and dispatch modelling, grid extension, market design as well as analysing environmental and social issues [7]. Still, most energy system modelling tools are proprietary [5, 8, 9]. However, the number of open source modelling tools increases [10] for reasons like transparency and public acceptance [8, 11], reproduceabillity [12] as well as improved productivity and quality of science [13].

Power system inertia in unit commitment and economic dispatch modelling is represented only superficial, if considered at all [14–16]. However, Johnson et al. conclude that unit commitment and dispatch models "[...] without a system inertia constraint are not fully capturing the impact of variable renewable energy on the generation mix" [14]. Additionally, "as grids integrate more renewable energy, relying on the current method of delivering inertia will see escalating costs, which demonstrates the value of integrating new sources of inertia, like synthetic inertia (SI) from wind turbines [...]" [14].

The previous paragraphs show the need for power system inertia consideration in unit commitment and economic dispatch modelling to assess future energy system pathways while maintaining sufficient power system inertia, the foundation for grid frequency controllability. To close this gap in the energy system modelling landscape, Open Inertia Modelling (OpInMod) is developed and presented in the work at hand. OpInMod is developed as part of a PhD project at the Wind Energy Technology Institute to assess costs in future power systems due to the provision of synchronous and SI. OpInMod optimises energy systems for the least cost unit dispatch to cover power demand while maintaining minimum system synchronous inertia and minimum system inertia over multiple periods. Incorporated sources for synchronous inertia are synchronously connected generators and synchronously connected storage units like synchronous condensers. Source for SI are WTs and inverter connected energy storage systems. Given the complexity of inertia consideration in energy system modelling tools and its novelty, transparency and accessibility are crucial to improve acceptance and discussion of the topic. Therefore, OpInMod is published as open source software under the MIT Licence and is free to inspect, modify, use and redistribute. OpInMod is available online on GitHub [17] and is archived on Zenodo [18]. Basic examples to present OpInMod's capabilities and functionality are provided via GitHub as well [19].

Implementation and Architecture

Inertia in Power Systems

Inertia is an essential part of grid frequency control [2] and its relevance increases with higher shares of non-synchronous penetration in power systems [1, 20]. The following part introduces the basics of synchronous inertia, concepts of providing SI and the role of inertia in future power systems. Such a detailed introduction is necessary to understand approaches and assumptions made in OpInMod.

Synchronous Inertia In AC-power system power balance has to be maintained at all times [21]. If power generation, P_{gen} does not match power consumption, P_{load}, the grid frequency, f_{grid}, which is the indicator for power balance and a direct representation of all synchronously connected rotating masses, deviates from its nominal value [21]. The speed with which the grid frequency changes, $\delta f/\delta t$, also reffered to as the Rate of Change of Frequency (ROCOF), is dominated by the overall systems moment of inertia, J_{sys} [2]. Equation (1) illustrates this relationship.

$$\frac{\delta f_{grid}}{\delta t} = \frac{P_{gen} - P_{load}}{4\pi^2 \cdot f_{grid} \cdot J_{sys}} \tag{1}$$

In the event of a power imbalance, synchronously connected rotated masses change their rotational velocity [2]. Kinetic energy, E_{kin}, is either stored in or released from the rotating parts of the synchronously connected machine [2]. Thereby, the grid frequency nadir is reduced [2]. An inherent inertial response is provided by all synchronously connected rotating masses from the power generation side and from the power consumption side as well [22].

The machines stored kinetic energy, $E_{kin,g}$, in the synchronously rotating parts is often expressed with respect to the machines apparent power rating, S_g, and referred to as the units inertia constant, H_g [2]. The inertia constant is the proportional expression, a unit is theoretically able to provide its rated power solely by its stored kinetic energy [2]. Depending on the fuel and generator type, the inertia constant typically is in the range of 2 s and 10 s [21, 23]. The following equation describes this relationship were J_g is the units moment of inertia and ω_g its rotational velocity [2].

$$H_g = \frac{E_{kin,g}}{S_g} = \frac{J_g \cdot \omega_g^2}{2S_g} \tag{2}$$

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Synthetic Inertia As already introduced, RESs like PVs and WTs are connected to the power system via grid frequency inverters [2]. The same applies for battery storage units [4]. Hence, even if rotating parts exist as in the case of WTs or high-speed flywheels, these units are electrically decoupled from the power system and do not provide an inherent response in the event of a power imbalance [2]. However, inverter connected generation and storage units are able to mimic the behaviour of a synchronous machine [1, 2, 20]. This is known as synthetic inertia, emulated inertia, virtual inertia or artificial inertia [20]. In this work the term synthetic inertia (SI)will be used further on only. For clarification purposes, SI in this work is defined as the "[...] controlled contribution of electrical torque from a unit that is proportional to the RoCoF [...]" [20]. In contrast, the grid frequency service fast frequency response is defined as the "[...] controlled contribution of electrical torque from a unit, which responds quickly to frequency changes to counteract the effect of a reduced inertial response." [20]. These two definitions are necessary, because in literature fast frequency response is also often referred to as SI [1, 20].

Due to the electric decoupling, the moment of inertia, J_{synt}, which is emulated, is freely selectable with respect to the source of energy as well as to the limits of the device [2]. In general, the power of a synchronous machine in the event of a power imbalance is determined by the following equation [4].

$$P_{inertia,g} = J_g \cdot 4\pi^2 \cdot f_{grid} \cdot \frac{\delta f}{\delta t} \tag{3}$$

By increasing J_{synt}, the unit providing SI is able to supply a higher power output as well as exchange more energy with the power system [2]. More detailed approaches of providing SI using energy storage units are presented in [2] and [20].

A common approach to provide SI with WTs is to adapt the electrical torque based on the ROCOF and change the rotors rotational speed [2]. Hence, similar to synchronous machines kinetic energy is either stored in or released by accelerating or decelerating the WT's rotor [2]. However, this causes the WT to operate at non-optimal rotational speeds and in some cases lead to the disconnection of the WT [24]. Limitations of providing SI with WTs are discussed in [25]. Gloe et al. introduced an approach which prevents the WT from disconnecting from the power system due to non-optimal operating points [24]. The authors propose to scale the WTs SI provision with the actual rotational speed, $\omega_{actual,WT}$, considering the rotors cut-in speed, $\omega_{cut-in,WT}$ and adapt the provided inertia with the demanded inertia constant, H_{dem}. Equation (4) depicts the relationship.

$$H_{var} = H_{dem} \cdot \frac{0.5 \cdot J_{WT} \cdot (\omega^2_{actual,WT} - \omega^2_{cut-in,WT})}{0.5 \cdot J_{WT} \cdot (\omega^2_{rated,WT} - \omega^2_{cut-in,WT})} \tag{4}$$

The demanded inertia constant is described by the system operator and tailored to power system requirements [24]. This control approach is called variable inertia constant, H_{var}, and detailed in [24]. The actual inertial response and power feed-in is determined by the ROCOF and f_{grid} as described by the following equation [24].

$$P_{SI,varH} = -2 \cdot H_{var} \cdot P_{rated} \cdot \frac{ROCOF}{f_{grid}} \tag{5}$$

Overall, the risk of disconnecting the WT while providing SI is reduced to a minimum [24]. This is in the interest of the system operator because the WT being a reliable source for power feed-in and SI [24].

Power System Inertia It is common practice to express the overall inertia within power systems via the power system inertia constant, H_{sys} [2]. Equation (6) describes the power system inertia constant where $E_{kin,sys}$ is the accumualted stored kinetic energy of all synchronously connected rotating masses and S_{sys} the overall apparent power.

$$H_{sys} = \frac{E_{kin,sys}}{S_{sys}} = \frac{\sum H_g \cdot S_g}{\sum S_g} \tag{6}$$

Since more conventional power plants get replaced with RESs, the number of synchronously connected generators decreases. Hence, the power system inertia constant decreases as well. As introduced in the previous part, electrically decoupled generation and storage units are able to provide synthetic inertia. However, as such units do not provide an inherent inertial response, the power system inertia constant in systems with a synchronous inertia and a SIshare comprises as follows [2]:

$$H_{sys} = \overbrace{\frac{\sum H_{i,sync} \cdot S_{i,sync}}{\sum S_i}}^{\text{system synchronous inertia}} + \overbrace{\frac{\sum H_{i,synt} \cdot S_{i,synt}}{\sum S_i}}^{\text{system synthetic inertia}} \tag{7}$$

As indicated by equation (1), inherent inertia limits the ROCOF. However, units providing SI do not provide an instantaneous inertial response [20]. Hence, the ROCOF is limited by synchronous inertia only. For system security reasons, system operators of low inertia power systems, like the Irish Transmission System Operator (TSO) EirGrid, already specifiy a threshold value for the maximum allowable ROCOF [20, 26]. Hence, a certain minimum synchronous inertia, $J_{sync,min}$, is need to maintain the ROCOF within limitations. The grid frequency nadir has also be maintained within limitations [20]. Therefore, an overall level of system inertia is needed [4]. In conclusion, future power systems have to be maintained with a certain level of system inertia, $J_{sys,min}$, which composes of a minimum synchronous inertia share, $J_{sync,min}$ and, if not already satisfied, a remaining share of synthetic inertia, J_{synt}.

Open Inertia Modelling - OpInMod

Open Inertia Modelling (OpInMod) is a model generator for unit commitment and economic inertia dispatch modelling. OpInMod is written in Python 3. It inherits the logic, i.e. structure, classes and functionalities of the Open Energy Modeling Framework (oemof). Therefore, before describing OpInMods methodology, oemofs basics are presented in the following.

The open source modelling framework - oemof oemof is an energy system modelling framework for representation, modelling and analysis of energy systems [27]. It is developed with a strict open-source and non-proprietary philosophy. It enables users to create energy system representations using a generic graph-base foundation implemented an object-oriented programming methodology. The modelling framework is written in Python. GitHub is used to organise collaborational project development as well as for code hosting and bug tracking [28].

As introduced, the basic foundation of oemof is the graph-based representation of energy systems. The energy system consists of a set of nodes and edges. Nodes are further divided into buses and components. Edges represent inputs and outputs of all components and buses. Buses represent how components are tied together. Components can be further divided into sources, representing the source of an energy flow, sinks, representing energy consuming entities and finally, transformers, representing entities converting energy flows.

The library oemof.solph can be used to build mixed-integer linear optimisation problems [29]. Therefore, an energy system is created using components and buses. Each object has predefined objective expression terms, optimisation variables and individual constraints. The library provides additional classes of higher complexity like storage units. The overall optimisation function generally minimises costs of the energy system for a given time. The pyomo package [30] is used in oemof.solph to build all sets of functions. The optimisaion problem is solbed by an external solver.

Methodology OpInMod is designed to create unit commitment and economic dispatch optimisation problems to find the least cost solution in resource application on condition that power demand is satisfied and sufficient provision of system synchronous inertia and overall system inertia. The model generator OpInMod is written in Python 3, published under MIT License and available via GitHub [17] and archived on Zenodo [18].

By design, oemof has one optimisation variable type, the variable `flow`. OpInMod introduces a second optmisation variable type, the variable `source_inertia`. Traditionally, a synchronously connected rotating mass is either connected to the power system and provides its overall inertia or not. Therefore, the optimisation variable `source_inertia` is of the type binary.

Equation (8) expresses the objective function consisting of one mathematical term representing energy flow associated costs and one mathematical term representing costs associated with the provision of inertia. The first term inherits from oemof while the second term is generated by OpInMod. Independently from whether the unit g is providing inertia inherently or providing synthetic inertia, the dimensioning factor for the potential power provided (see Equation (3)) is the moment of inertia, $x_g^{inertia}$. The the unit of the moment of inertia is expressed in kg·m^2 and costs, c_g^{ic}, associated with the provision of inertia in EUR/kg·m^2. The binary optimisation variable `source_inertia` is represented by $x_g^{source\_inertia}$.

$$\min : \sum_t \sum_g \overbrace{c_g^{vc} \cdot x_g^{flow}(t)}^{\text{costs flow}} + \overbrace{x_g^{source\_inertia} \cdot c_g^{ic} \cdot x_g^{inertia}(t)}^{\text{costs inertia}} \tag{8}$$

Sufficient provision of system synchronous inertia and overall system inertia is assured by the constraints depicted by Equation (9) and (10).

$$x^{min\_sys\_sync\_inertia} \leq \sum_{g} x_g^{source\_inertia} \cdot x_g^{sync\_inertia} \tag{9}$$

$$x^{min\_sys\_inertia} \leq \sum_{g} x_g^{source\_inertia} \cdot (x_g^{sync\_inertia} + x_g^{synt\_inertia}) \tag{10}$$

Figure 1 depicts the structure of classes in OpInMod. Likewise to oemof, the class *EnergySystem* functions as a container for elements such as nodes and edges and carries information like the time series [27]. Added to the class are the attributes `nominal_grid_frequency`, which is an information needed to calculate the moment of inertia (see Equation (2)), `minimum_system_synchronous_inertia` and `minimum_system_inertia` to build the constraints described in Equation (9) and (10) and `emulated_inertia_constant`, which is the demanded inertia constant, H_{dem}, to determine the SI provision by WTs (see Equation (4)).

The class *Inertia* is designed to represent the inertia an unit is able to provide. The attributes `rated_power` and `provision_type` are mandatory. So is either the attribute `inertia_constant` or `moment_of_inertia`. OpInMod processes the units moment of inertia (see Equation (8)). Hence, if the attribute `moment_of_inertia` is not specified, it is calculated using the attribute `inertia_constant` and Equation (2) rearranged for J_g. So far, four different unit types providing inertia are incorporated: 'synchronous_generator', 'synchronous_storage', 'synthetic_wind' and 'synthetic_storage'. Based on the specified provision type, further attributes are needed. In the following, each provision type is presented as well as the then mandatory attributes and internal relations of the provision type with its resulting constraints. The attribute `inertia_costs` can be specified independently from the provision type. If not specified, it is initialised with zero. Hence, if costs are directly associated with the provision of synchronous or synthetic inertia, it is considered in the optimisation function (see Equation (8)).

Type: synchronous_generator The provision type 'synchronous_generator' represents any type of synchronously connected generator. When using this provision type, the attribute `minimum_stable_operation` has to be specified. Most generators have a minimum operating point needed for stable operation, $x_g^{min\_stable\_op}$, [16]. This point is expressed as a share of the rated capacity, $x_g^{rated\_power}$. The resulting constraint is described by Equation (11).

$$x_g^{flow} \geq x_g^{source\_inertia} \cdot x_g^{min\_stable\_op} \cdot x_g^{rated\_power} \tag{11}$$

If a synchronous generator is connected to the power system, inherent inertia is provided. This relation results in a constrained expressed in Equation (12).

$$x_g^{source\_inertia} \geq \frac{x_g^{flow}}{x_g^{rated\_power}} \tag{12}$$

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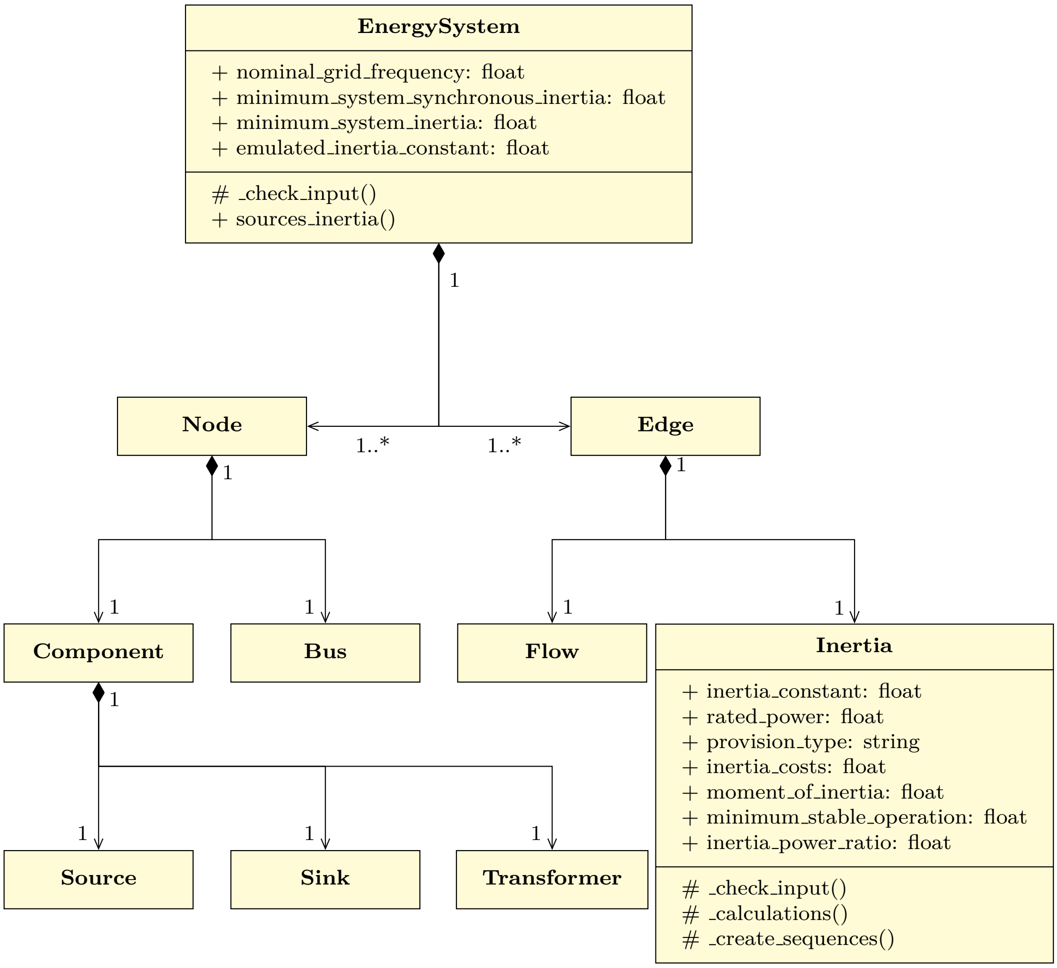

Figure 1: Extract of OpInMod classes depicted in an UML class diagram. All classes are inheritance from the oemof core. The class *EnergySystem* functions as a container for elements such as nodes and edges. The class *Inertia* is designed to represent the inertia an unit is able to provide.

Type: synthetic_wind The basic concept to provide SI with WTs as incorporated in OpInMod is introduced in paragraph **Synthetic Inertia**. Since the provision of SIby Gloe et al. is based on the actual operating point of a WT, normalised characteristics of the fully open source NREL 5MW WT are applied OpInMod [31]. The capacity factor input is used to determine corresponding normalised rotational speed of the WT. In the next step, the normalised rotational speed is used to determine the variable inertia constant, H_{var}, with respect to the demanded inertia constant, H_{dem}. This approach is visualised in Figure 2.

Having the determined variable inertia constant with respect to the demanded inertia constant, the actual provided synthetic inertia, $x_g^{synt\_inertia}$, of the WT can be calculated by multiplying this value with the system demanded inertia constant and apply this value to Equation(2) rearranged to J_g.

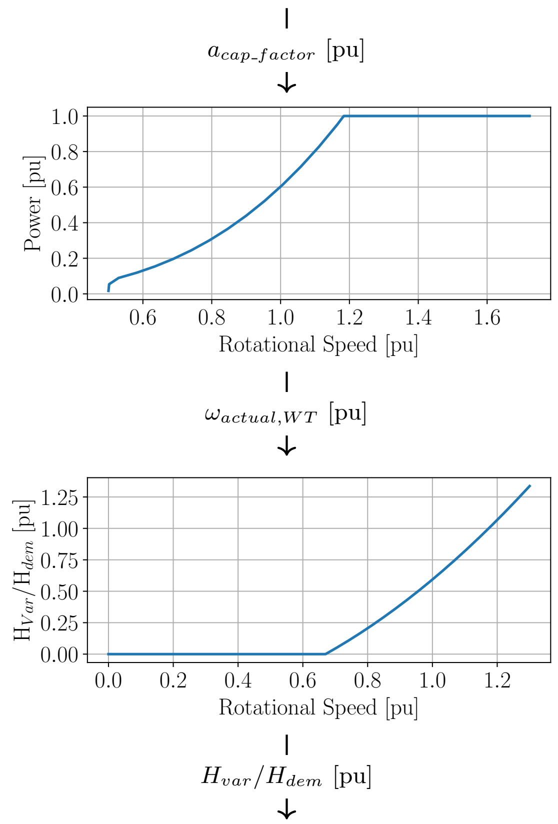

Figure 2: Two step methodology to determine H_{var}/H_{dem} applying the normalised rotational speed characteristic of the NREL 5MW WT [31] and the normalised characteristics of the variable H controller [24]. The normalised rotational speed is calculated based on the WT synchronous speed.

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Type: synchronous_storage The third predefined provision type in OpInMod is named 'synchronous_storage' an represents units like synchronous condensers [32]. Synchronous condensers have no real power output and are used for reactive power compensation in power systems and the provision of inertia. Hence, their only purpose in OpInMod is the provision of synchronous inertia.

Type: synthetic_storage Different types of storage units can be applied to provide SI [4, 20]. Therefore, the provision type 'synthetic_storage' can be implemented as a source for inertia. The attribute `inertia_power_ratio` is then mandatory to be specified. It the ratio between the storage units power output to cover power demand and the potential power output in the event of a power imbalance. Hence, the emulated inertia power response. Similar to the approach of providing grid frequency services like fast frequency response or primary frequency control with WTs and de-loading the units power output [32], the storage units power output is de-loaded as well. Hence, the power reserve can be used to provide synthetic inertia. For example, an `inertia_power_ratio` of 0.4 results in a potential SIpower output of 40 % of the units rated power. 60 % of the units rated power can be potentially used in optimisation problem to satisfy power demand. The emulated moment of inertia is then calculated by rearranging Equation (3).

Quality control

OpInMod comes with a set of four examples via GitHub which can be used to test and learn the basic functionalities of the model generator [19]. Users can raise any kind of issue in the GitHub repository [17, 19]. The first example consists of four fossil fuel commodities (hard coal, lignite, oil and natural gas) and the respective transformers to cover power demand. Each of the examples is extended by first, a PV and WT source, second, by a synchronous condenser and finally, by a battery storage unit. A schematic illustration of the four examples is depicted in Figure 3 as a network consisting of components and buses. The colored frames depict the composition of the respective example. The flow results are illustrated in Figure 4 and Figure 5 depicts the provision of snychronous and synthetic inertia. Table 1 shows the accumulated flow results and the CO_2 emissions per example. The follow paragraphs sum up the results of the four examples.

The top left subplot in Figures 4 and 5 depict the results of the first example. Demand is satisfied by the lignite, hard coal and natural gas fired transformers. The power production dip of the hard coal transformer is due to the minimum stable production constraint (see Equation (9)) of the natural gas fired transformer. Provision of synchronous inertia is constant for almost the entire modelling period, except for the peak demand hour where the oil fired transformer is connected to the power system to satisfy demand. During this modelling time step the power system inertia constant dips, due to the higher overall apparent power (compare Equation (7)).

The top right subplot in Figures 4 and 5 depict the results of the second example. The second example is extend by a WT and PV source. The WT source provides synthetic

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inertia. The second example is dominated by potential WT and PV production which in sum surpass power demand. Hence, excess electricity increases significantly. Although, accumulated WT and PV electricity generation would be high enough to satisfy power demand, transformers with synchronously connected generators run at minimum stable generation levels to due to the minimum needed system synchronous inertia. Obviously, the combined synchronous and SI provision by the WT source surpass the overall needed system inertia.

The bottom left subplot in Figures 4 and 5 depict the results of the third example. A synchronous condenser is added to the example as a potential source for synchronous inertia. WT and PV power production is used only to cover power demand. The minimum synchronous inertia constraint is satisfied by the synchronous inertia provision of the synchronous condenser. This is reflected by less excess electricity and less CO_2 emissions (see Table 1). The overall system inertia constraint is satisfied by the SI provision of the WT.

The bottom right subplot in Figures 4 and 5 depict the results of the fourth example. The final example is extended by a battery storage unit which is a potential source for SI and to cover power demand. The application of the battery storage units results in less power feed-in from fossil fuel fired transformers and less excess power generation.

Table 1 sums up the results of each example. For each example, the overall production by fossil fuel generation, RES generation, excess generation and CO_2 emissions are presented. The results indicate, that the integration of alternative sources of inertia like WTs, synchronous condensers and battery storage units decrease the overall excess integration and CO_2 emissions.

Table 1: Results

	Fossil [MWh]	RES [MWh]	Excess [MWh]	CO_2 [t]
Example 1	2 667.895	0	0	1 686.515
Example 2	1 120.058	2 214.913	667.047	753.937
Example 3	907.805	2 214.913	454.793	625.516
Example 4	812.806	2 214.913	404.793	563.083

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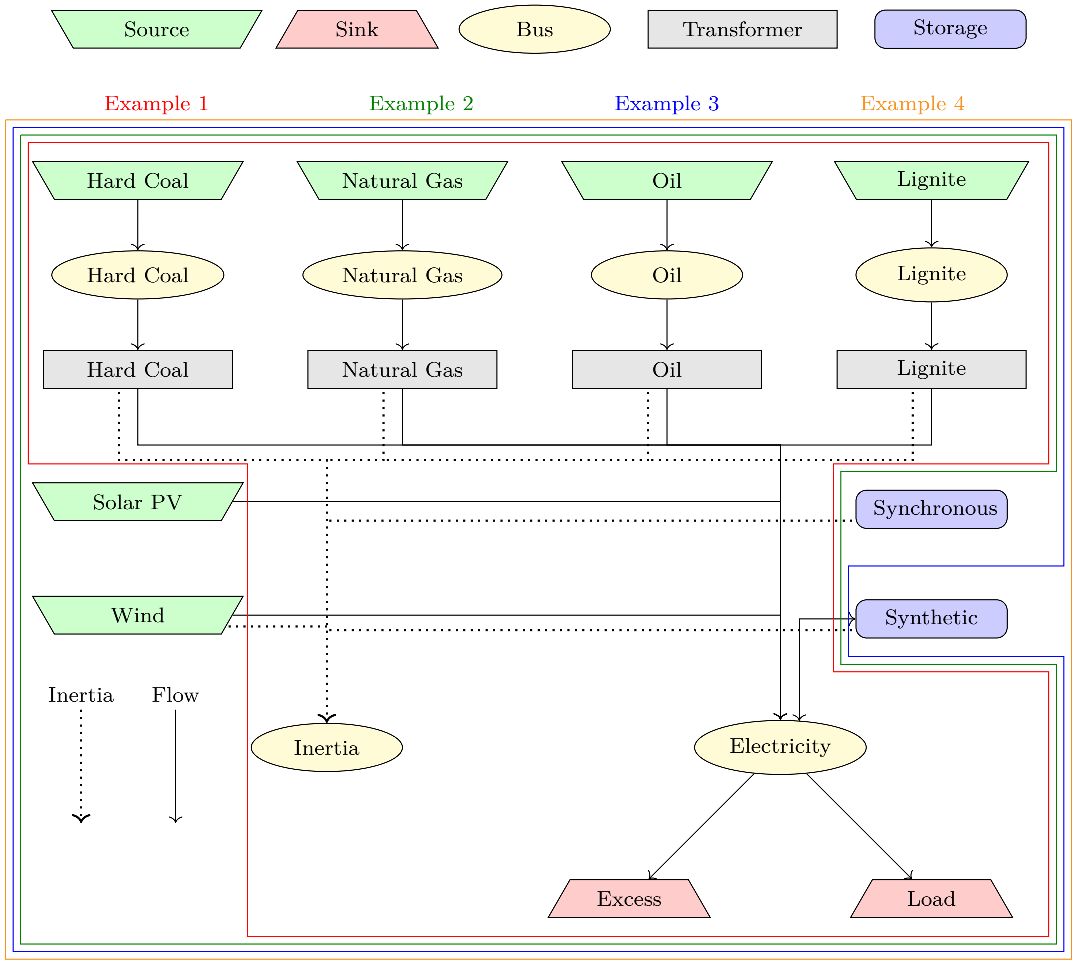

Figure 3: Example overview. Each combination of entities is indicated by a colored frame

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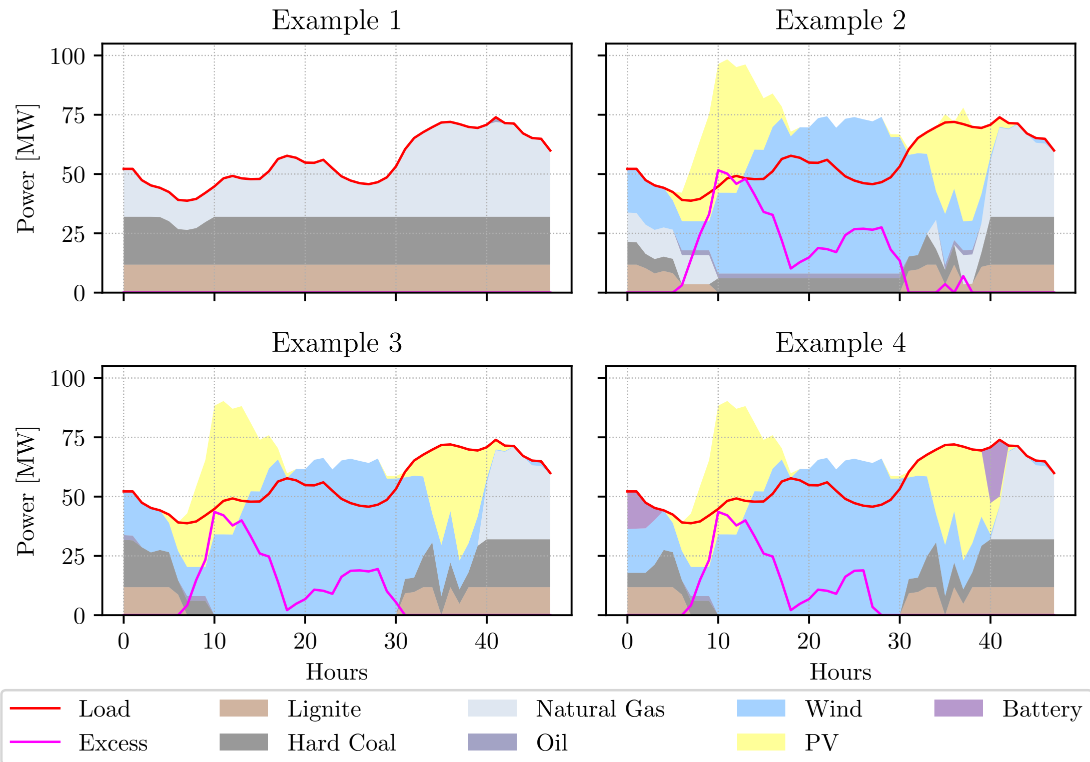

Figure 4: Depiction of the power flow results of the four OpInMod example. As indicated by the title, each sub-figure illustrate the results of one example.

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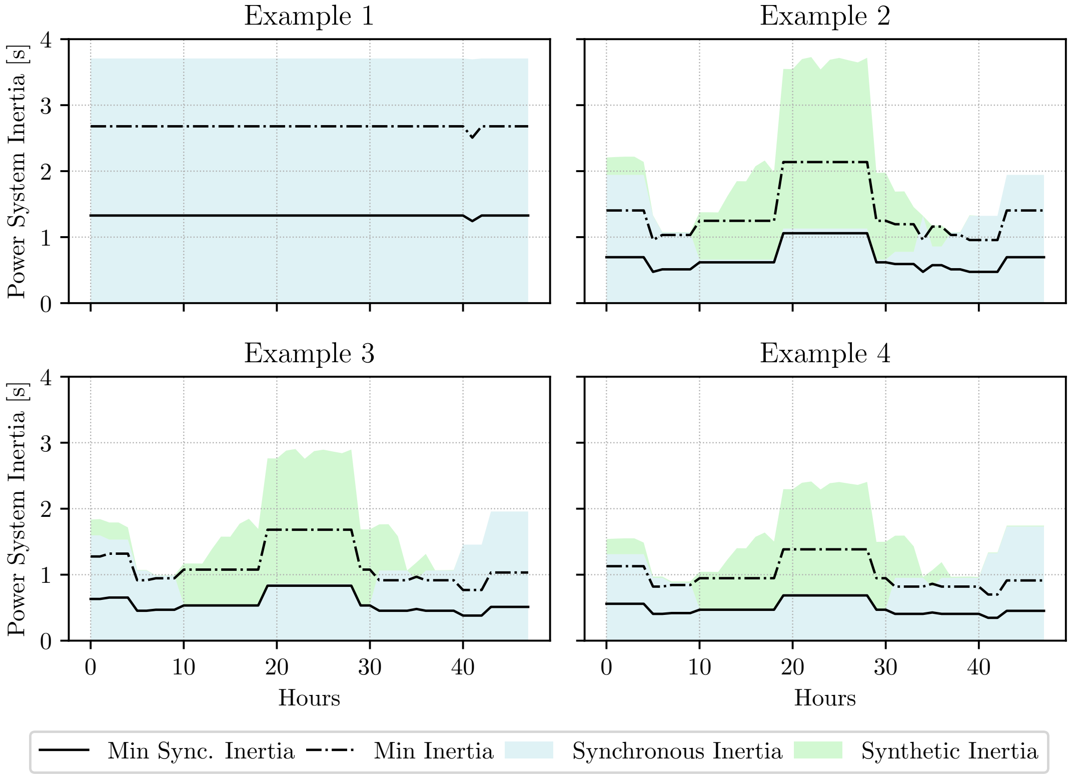

Figure 5: Depiction of the inertia results of the four OpInMod example. As indicated by the title, each sub-figure illustrate the results of one example.

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(2) Availability

Operating system

GNU/Linux, Mac OSX, Windows and any other operating systems running Python 3.

Programming language

OpInMod is written in Python 3.8.10

Additional system requirements

None

Dependencies

OpInMod depends on the following Python libraries. The version number, if not part of the Python standard library, is specified for which OpInMod is tested.

- Pyomo = 5.7.2, [33]
- pandas = 1.3.2, [34]
- scipy = 1.7.1, [35]
- math
- os
- oemof.solph = 0.4.4, [29]

Since OpInMod inherits oemof.solph, the following additional Python libraries are needed to to run oemof

- blinker = 1.4, [36]
- dill = 0.3.4, [37]
- numpy = 1.21.2, [38]
- networkx = 2.6.2, [39]
- oemof.tools = 0.4.1, [27]
- oemof.network = 0.4.0, [27]

Software location:

Archive

Name: Zenodo

Persistent identifier: https://doi.org/10.5281/zenodo.5582502

Licence: MIT License

Publisher: Zenodo
Version published: 0.1
Date published: 19/10/2021

Code repository

Name: GitHub
Persistent identifier: https://github.com/hnnngt/OpInMod.
Licence: MIT License
Date published: 19/10/2021

Language

English

(3) Reuse potential

Controllability of low inertia power systems is an issue of increasing interest for system operators [3, 26, 40] and the research community [1, 2, 20]. With OpInMod being the first open source modelling tool able to model SI by WT and battery storage units as well as including the provision of inertia by synchronous condensers there is a high reuse potential for energy system modellers. To increse reuse potential, OpInMod is designed with a universal approach. OpInMod being an open source tool decreases the initial hurdle for modellers while extending the number of potential users.

Support and an introduction to OpInMod's functionality is provided via the GitHub repository [17, 19].

User can contribute to code development and improvement, raising issues or making pull requests on the GitHub repository [17].

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