EUROPA-UNIVERSITÄT FLENSBURG

An Assessment of Costs for System Inertia in Future Power Systems consisting of a high Share of Non-Synchronous Penetration

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Abstract

The need to limit global warming by decarbonising power systems drives the replacement of fossil fuel-fired power plants with renewable energy sources. For the most part, with frequency converter connected wind turbines and photovoltaic systems. As a result, power system inertia decreases. To maintain the controllability of the grid frequency, countermeasures need to be taken, which are associated with costs. This work assesses costs for system inertia in future power systems with a high share of non-synchronous penetration.

Publications part of this cumulative thesis are categorised into three phases. The first phase assesses the basics of system inertia and defines fundamental assumptions. In the second phase, single topics such as load inertia, inertia provision via the day-ahead market and the influence of synthetic inertia provided by wind turbines on the power system are assessed. The last phase combines previous findings and analyses system costs of the future German power system due to the provision of inertia.

In the Continental European power system, non-synchronous flywheel systems are the least-cost solution to provide necessary synthetic inertia with total annual costs of 167.64 €/(kg·m^2). Currently, load inertia accounts for 20 % of the total system inertia and contribution of different consumer groups varies significantly. Securing sufficient system inertia in the Irish power system via the day-ahead market results in additional operating costs ranging from 1.02 €/(kg·m^2) to 4.49 €/(kg·m^2). Wind turbines can provide continuous inertia and are thus able to reduce must-run capacities and resulting CO_2 emissions in the Irish power system by 31 %, curtailment by 40 % and system costs by 33 %. Results indicate costs in future German power systems for inertia provision in the range from 0.002 €/(kg·m^2) to 0.61 €/(kg·m^2). Wind turbines and synchronous condensers equipped with flywheels providing inertia are the most cost-efficient solution to maintain the controllability of the grid frequency in future power systems. Higher CO_2 certificate prices need to be taken into account to achieve overall decarbonisation targets. Further, reduction of primary power reserves activation time is crucial.

List of Publications

Publications part of the doctoral cumulative thesis:

Publication I	H. Thiesen, C. Jauch, and A. Gloe, “Design of a System Substituting Today’s Inherent Inertia in the European Continental Synchronous Area,” Energies, vol. 9, no. 8, p. 582, Jul. 2016, doi: 10.3390/en9080582.
Publication II	H. Thiesen and C. Jauch, “Determining the Load Inertia Contribution from Different Power Consumer Groups,” Energies, vol. 13, no. 7, p. 1588, Apr. 2020, doi: 10.3390/en13071588.
Publication III	H. Thiesen and C. Jauch, “Application of a New Dispatch Methodology to Identify the Influence of Inertia Supplying Wind Turbines on Day-Ahead Market Sales Volumes,” Energies, vol. 14, no. 5, p. 1255, Feb. 2021, doi: 10.3390/en14051255.
Publication IV	H. Thiesen and C. Jauch, “Potential of Onshore Wind Turbine Inertia in Decarbonising the Future Irish Energy System,” Appl. Sci., vol. 12, no. 6, p. 2984, Mar. 2022, doi: 10.3390/app12062984.
Publication V	H. Thiesen, “Power System Inertia Dispatch Modelling in Future German Power Systems: A System Cost Evaluation,” Appl. Sci., vol. 12, no. 16, p. 8364, Aug. 2022, doi: 10.3390/app12168364.

Further publications

Journal Paper	C. Jauch, A. Gloe, S. Hippel, and H. Thiesen, “Increased Wind Energy Yield and Grid Utilisation with Continuous Feed-In Management,” Energies, vol. 10, no. 7, p. 870, Jun. 2017, doi: 10.3390/en10070870.
Conference Publications	A. Gloe, H. Thiesen and C. Jauch, “Grid frequency analysis for assessing the stress on wind turbines,” in Proc. 15th Wind Integration Workshop, Vienna, Austria, 2016.
	H. Thiesen, A. Gloe, J. Viebeg and C. Jauch, “The Provision of Synthetic Inertia by Wind Turbine Generators: An Analysis of the Energy Yield and Costs,” in Proc. 16th Wind Integration Workshop, Berlin, Germany, 2017.
	H. Thiesen and C. Jauch, “A dispatch methodology to secure power system inertia in future power systems,” in Proc. 17th Wind Integration Workshop, Stockholm, Sweden, 2018.
	H. Thiesen and C. Jauch, “Identifying electromagnetic illusions in grid frequency measurements for synthetic inertia provision,” in Proc. 2019 IEEE 13th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG), Sønderborg, Denmark, 2019, pp. 1-6, doi: 10.1109/CPE.2019.8862311.
Preprint	H. Thiesen, “Open Inertia Modelling (OpInMod) - An Open Source Approach to Model Economic Inertia Dispatch in Power Systems,” Preprints, 2022, 2022010419, doi: 10.20944/preprints202201.0419.v1.
Technical Reports	A. Gloe, C. Jauch, H. Thiesen and J. Viebeg, “Inertial Response Controller Design for a Variable Speed Wind Turbine,” WETI, Flensburg, Germany, 2018, doi: 10.13140/RG.2.2.27846.57926.
	S. Hippel, H. Thiesen and C. Jauch, “Regelbares Schwungrad in einem Rotor einer Windenergieanlage zur Unterstützung der Netzfrequenzregelung,” WETI, Flensburg, Germany, 2015, doi: 10.13140/2.1.3076.8166.

Popular Scientific Publications	C. Jauch, H. Thiesen and A. Gloe, “Der Wert der Systemträgheit im Stromnetzvor dem Hintergrund der Energiewende,” Ingenieurspiegel, vol. 4, no. 2, 2015.
Software	*Open Inertia Modelling (OpInMod),* (2021), H. Thiesen, Zenodo, Oct. 19, 2021. doi: 10.5281/zenodo.5582502. *Open Inertia Modelling (OpInMod),* (2021), H. Thiesen, Github, Oct. 19, 2021. Accessd: Nov. 2022. [Online]. Available: `https://github.com/hnnngt/OpInMod`.
Data	*Grid Frequency Data – WETI,* H. Thiesen, A. Gloe and C. Jauch, osf.io, 2021, doi: 10.17605/OSF.IO/JBK82.

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List of Abbreviations

ENTSO-E	European Network of Transmission System Operators for Electricity
FFR	Fast Frequency Response
LCOI	Levelised Costs of Inertia
NPV	Net Present Value
O&M	Operation and Maintenance
OpInMod	Open Inertia Modelling
RES	Renewable Energy Sources
ROCOF	Rate of Change of Frequency
SI	Synthetic Inertia
TSO	Transmission System Operator

1 Introduction

Energy systems are decarbonised to reduce the risks and consequences of the anthropogenic climate change. Leaders of the UN member countries agreed to limit global warming to well below 2 °C with regard to pre-industrial levels, further aiming for a limitation of below 1.5 °C [1]. Therefore, fossil fuel-fired power plants are being replaced by Renewable Energy Sources (RES) like hydro plants, wind turbines, photovoltaic systems and biomass plants. The replacement of fossil fuel-fired power plants with large installed capacities of volatile RES challenges power system operators and power markets as well as authorities [2, 3].

The introduction of RES into power systems imposes considerable challenges on grid frequency stability [2]. In isolated AC power systems, power generation and power consumption including grid losses have to be balanced at all times [4]. The indicator for this balance is the grid frequency. An imbalance of power generation and power consumption leads to a deviation of the grid frequency from its nominal value. The speed with which the grid frequency changes, commonly referred to as the Rate of Change of Frequency (ROCOF), and the absolute grid frequency nadir or peak are determined by power system inertia [2].

Power system inertia is provided by synchronously connected rotating masses like generators and motors [2]. State-of-the-art wind turbines and photovoltaic systems are connected to the power system via frequency converters [2]. Hence, even if a rotating mass exists, as in the case of wind turbines, their inertia is hidden from the power system. However, power system inertia is essential for maintaining grid frequency stability; it limits the ROCOF. Thus, units supplying an active power reserve are provided with the necessary time to adapt power output to re-establish the balance between power generation and power consumption [2]. This is vital because these units are not able to adapt power output instantaneously. If the ROCOF or the absolute grid frequency nadir or peak exceeds specified thresholds, generators or loads get disconnected from the power system which ultimately results in a system blackout [5].

Inertia is a by-product of conventional power generation, yet remains free of charge, despite being essential for grid frequency stability. Since more fossil fuel-fired power plants are being replaced by a large number of non-inertia-providing RES, not only technical but also economic assessments and solutions are required to maintain future power system stability.

1.1 Status Quo

Decreasing power system inertia and resulting challenges to maintain controllability of the grid frequency already occur in smaller and medium-sized power systems. The following overview summarises current challenges imposed on and actions taken by Transmission System Operators (TSOs) due to low system inertia and actions taken as a countermeasure.

The grid operator of Hydro-Québec required wind turbines to provide an inertia response with characteristics similar to those of a synchronously connected generator in the event of a power imbalance [6, 7]. Current wind turbines in the synchronous grid of Hydro-Québec are obligated to provide a very fast-responding active power reserve [8]. For synchronously connected generating units, the inertia constant within the generating station has to be compatible with the inertia constant of the already existing generating units [8]. Additionally, the TSO is allowed to specify a minimum inertia constant which applies to generating units within generating stations [8].

Australia has a power system which is highly decentralised with load and generation centres in distant locations [9]. Transmission capacities between regions are limited and especially the regions of South Australia and Tasmania are characterised by times with a high share of non-synchronously connected generation units, mostly photovoltaic systems [9]. Thus, the Australian TSO has introduced inertia requirements to maintain a secure and efficient operation of its power system [10]. The requirements include a minimum inertia threshold in case a region is operated in island mode or in case of a credible risk of separation [10, 11]. The current regulation does not value inertia economically [12]. Neither in an operational nor in an investment timeframe does the regulation result in transparent price signals [12].

Another power system characterised by a high share of non-synchronous generation units is the all-Island Irish power system [13]. Feed-in from wind turbines is already curtailed due to low power system inertia, 1,169 MWh overall in 2019 [14], 1,945 MWh in 2020 [15] and 1,423 MWh in 2021 [16]. Compared to the annual overall feed-in from wind turbines, these numbers are rather low and account for less than 1 % of the annual wind feed-in. Nevertheless, wind turbine feed-in is curtailed in favour of thermal power generation for the sake of securing a sufficient level of system inertia. The Irish TSO has specified operational constraints to secure power system stability [13]. Specified are the maximum non-synchronous penetration of 65 %, an operational limit of the ROCOF of 0.5 Hz/s measured over a rolling window of 500 ms, as well as an operational threshold of inertia of at least 23 GWs [13, 17].

In 2019 the TSO of Great Britain introduced the Stability Pathfinder program [18]. Within the framework of that program, a tender has been launched to find the most cost-effective solution to increase the synchronous inertia level across Great Britain [18]. The tender resulted in an overall purchased inertia of 16.8 GWs for £ 574.6 million and a provision period of six years [19].

During the COVID-19 pandemic, the power system of Great Britain was characterised by times of low power demand and a high share of non-synchronous RES penetration leading to low system inertia between May and July 2020 [20]. During that time period, the TSO had to purchase additional system services with costs approximately three times higher compared to the previous year - £ 302 million compared to £ 101 million [20].

The paragraphs above highlight challenges associated with the operation of low-inertia power systems. Although inertia has been a free-of-charge by-product of conventional power generation, the operation of future power systems with a high share of non-synchronous penetration and necessary countermeasures to maintain grid frequency stability are associated with costs. Operators of units providing an inertia response will demand compensation for their expenditures associated with the ancillary service inertia.

1.2 Research Question

Considering the context introduced above, the work at hand aims to answer the following research question:

What are the costs associated with the provision of inertia in future power systems consisting of a high share of non-synchronous penetration?

The question stated above will be guided by the following sub-questions.

1. What would be the appropriate unit to economically value costs for system inertia and thus be the trading unit for inertia in future power systems?
2. Is it possible to further assess and evaluate the inertia contribution from power consumers?
3. Is Synthetic Inertia supplied by wind turbines able to provide a significant contribution to maintain grid frequency stability?

1.3 Structure of Dissertation

This dissertation is split into five chapters. Chapter 1 introduces the topic. In Chapter 2 the overall foundations of grid frequency stability and power system inertia as well as alternative sources for inertia provision in future power systems are introduced. Furthermore, relevant literature with regard to the research topic is reviewed. The publications part of this cumulative dissertation are summarised in Chapter 3 with a focus on the presentation of the results of each single work. The publications of this thesis can be categorised into three research phases of which the first publication introduces the topic within the context of this dissertation (Phase I), the second, third and fourth publication focus on individual issues related to low inertia power systems and solutions (Phase II) and the fifth publication, building upon findings of the previous publications, answers the research question (Phase III). The results of this thesis are presented and discussed in Chapter 4. Chapter 5 concludes the work.

2 Foundations

This chapter provides an overview of the foundation of inertia. Therefore, current grid frequency control measures and the functionality of inertia itself are reviewed. Alternative sources for a synchronous and non-synchronous inertia response are introduced. The chapter concludes with a literature overview of publications regarding power system inertia. A final focus is directed towards the economic aspects of power system inertia.

2.1 Grid Frequency Control

Power generation and power consumption including grid losses in isolated AC power systems have to be balanced at all times [4]. The indicator for such balance is the grid frequency, f_{grid} [4]. The grid frequency is a representation of the rotational speed of all synchronously connected rotating masses in the system. In case of an imbalance between power generation and power consumption, the grid frequency deviates from its nominal value. The following example details the grid frequency control measures in the event of a sudden loss of power generation, e.g., the tripping of a generator. The example details measures taken in the Continental Europe power system specified by the European Network of Transmission System Operators for Electricity (ENTSO-E) [5].

The tripping of a generator leads to an imbalance between power generation and power consumption. In this case, power consumption surpasses power generation. Thus, the grid frequency decreases. The deviation of the grid frequency from its nominal value has to be limited within defined thresholds. The upper threshold is specified at 51.5 Hz and the lower threshold at 47.5 Hz. In case thresholds cannot be met, either generation units or loads are disconnected from the system in order to re-establish power balance. In the case of grid frequency decreasing below 49 Hz, stepwise load shedding is activated. Primary control reserves are activated, and additional power is provided when the grid frequency deviation exceeds ± 20 mHz of the nominal value of 50 Hz. The reserve has to be fully activated within 30 s of detection of the event and a power reserve has to be delivered for a minimum duration of 15 min. The overall purpose of primary control reserves is to stabilise the grid frequency and re-establish the balance between power generation and consumption. Further measures are the activation of secondary and tertiary control reserves to release primary reserves. These measures will not be further detailed in this work.

Inverted measures to those in the example described above, are activated in the event of power generation surpassing power consumption. In this case, negative power reserves are activated.

The initial speed with which the grid frequency changes is determined by power system inertia [2]. Further, inertia provides time to units supplying primary reserve services. Power system inertia is a passive control reserve provided by synchronously connected rotating masses. The following section details the foundations with regard to system synchronous inertia.

2.2 Synchronous Inertia

In general, inertia describes the resistance of a moving object to changes in its state of motion, including directional changes and changes in its velocity [2]. In terms of power systems, inertia refers to the stored kinetic energy of any synchronously connected rotating mass [21].

Referring to the example in Section 2.1 - introducing grid frequency control reserves - the tripping of a generator results in a decreasing grid frequency. Thus, stored kinetic energy of the rotational motion of a synchronously connected mass is released and fed into the power system. Thereby, the speed with which the grid frequency changes, commonly referred to as the Rate of Change of Frequency (ROCOF), decreases. Equation (2.1) depicts this relation with $\delta f_{grid}/\delta t$ being the ROCOF, ΔP_{grid} representing the power imbalance, f_{grid} the grid frequency and J_{sys} representing the overall system inertia [2].

$$\frac{\delta f_{grid}}{\delta t} = \frac{\Delta P_{grid}}{4 \cdot \pi^2 \cdot f_{grid} \cdot J_{sys}} \tag{2.1}$$

The stored kinetic energy, $E_{i,kin}$, of the synchronously connected rotating mass, i, can be calculated as described via Equation (2.2), in which J_i is the generator's moment of inertia.

$$E_{i,kin} = \frac{1}{2} \cdot J_i \cdot 4 \cdot \pi^2 \cdot f_{grid}^2 \tag{2.2}$$

The overall power system inertia is calculated as depicted in Equation (2.3).

$$J_{sys} = \sum J_i \tag{2.3}$$

The stored kinetic energy of a synchronously connected rotating mass is commonly also expressed via the object's inertia constant, H_i [4]. The inertia constant describes the theoretical time a synchronously connected rotating mass is able to provide its nominal power with its stored kinetic energy only [2]. It is the proportional expression of the stored kinetic energy with respect to the unit's nominal apparent power, S_i, as depicted in Equation (2.4).

$$H_i = \frac{E_{i,kin}}{S_i} \tag{2.4}$$

For the sake of simplicity, it can be assumed that the nominal apparent power equals the nominal active power. The robustness of a power system in terms of the inertia contribution is described via the system inertia constant, H_{sys}, and described in Equation (2.5) [2].

$$H_{sys} = \frac{\sum H_i \cdot S_i}{\sum S_i} = \frac{\sum E_{i,kin}}{\sum S_i} \tag{2.5}$$

2.3 Non-Synchronous Inertia

State-of-the-art Renewable Energy Sources (RES) such as wind turbines and photovoltaic systems, as well as most energy storage units, are connected to power systems via frequency converters [2]. Hence, these units are electrically not directly coupled to the power system and, in contrast, to synchronously connected rotating masses, do not provide an inherent inertia response in the event of a power imbalance. However, kinetic energy is stored in some of these units or energy is stored in other forms.

Frequency converter connected generation and energy storage units are able to mimic the behaviour of a synchronously connected rotating mass in the event of a power imbalance by applying control strategies [2]. Such a service is commonly referred to as Synthetic Inertia (SI) [22]. Literature also refers to SI as emulated inertia, virtual inertia or digital inertia [23]. SI within the scope of this dissertation is defined as the controlled proportional contribution of the unit's electrical torque with regard to the ROCOF [22]. In contrast, a conventional grid frequency response as introduced in Section 2.1 or Fast Frequency Response (FFR) which is a faster-responding reserve compared to primary control reserves, is defined to be the controlled contribution of the electrical torque with regard to the grid frequency deviation [22].

SI is not a direct substitution for inherent synchronous inertia [2]. Energy is not directly absorbed or released with respect to the ROCOF as in the case of synchronously connected rotating masses [23]. First, the ROCOF needs to be detected by a measurement system and second the electrical torque needs to be adapted by the controller [2, 23]. Due to this delay in time, synchronous inertia is not fully substitutable by a non-synchronous response as SI [2, 24].

2.4 Literature Review

The following literature review summarises publications addressing the topic of system inertia in power systems. Reviewed are publications presenting a general overview of inertia in power systems, alternative sources and its control methods to provide an inertia response, system inertia in future systems as well as economic aspects of inertia provision.

Many publications provide a general overview of the topic of inertia in power systems. Taking the perspective of a grid operator, Tielens and Van Herten present the general functionality of synchronous inertia in power systems, discussing potential solutions in systems with decreasing inertia as well as introducing a new definition of system inertia in future power systems consisting of a synchronous and non-synchronous share [2]. The implications of low inertia power systems on the ROCOF in small and large island power systems as well as in large, interconnected power systems are presented by Hartmann et al. [24]. Alternative solutions as opposed to inertia provision from conventional power plants such as SI and synchronous condensers as a source for inertia are presented as well as an overview of commercialisation efforts of inertia-related services by system operators. A general introduction to the topic of system inertia is given by Makolo et al. focusing their review on monitoring and estimation methods [23]. Focusing on United States power systems, Denholm et al. presented an introduction of the topic of inertia in power systems to educate policymakers and further interested stakeholders [21].

Currently, an inherent inertia response is, to a large extent, provided by synchronously connected generators of fossil fuel-fired power plants [2]. The inertia constant of such units ranges from 2 to 9 s for thermal generation units, 2 to 6 s for AC wind turbines, 2 to 4 s for hydro generation units and 3 to 4 s for compressed air energy storage plants [25].

Synchronous inertia is not only provided by synchronously connected generators but by all synchronously connected rotating masses. This also includes the provision of inertia supplied by synchronously connected masses from power consumers [2]. Tavakoli et al. evaluated grid frequency and generator output signals of the Irish power system and concluded the load inertia contribution to be in the range of 0.1 to 1.1 s [26]. The demand side inertia contribution in Great Britain is 1.75 s on average, which represents around 20 % of the overall system inertia [27]. However, like the general development of synchronous inertia provided by generators in power systems, it is assumed that inertia contribution from synchronously connected loads is decreasing too due to the increasing connection of variable speed drives on the power consumption side [28].

As introduced in Section 2.3, frequency converter-connected RES and energy storage units are able to provide SI. A common strategy to provide SI with wind turbines is to adapt the electrical torque of the wind turbine and thus, either release or absorb kinetic energy from the wind turbines rotor and its rotating components [29]. As a consequence, the wind turbines rotor potentially rotates at an aerodynamically sub-optimal operating point. Thus, after adapting the power output and providing SI, the rotational speed has to recover and feed-in decreases. In the worst case, the wind turbine disconnects due to over or under-speed protection while providing SI. By scaling the SI response with the actual operating point of the wind turbine, disconnection of the generation unit can be avoided [30]. An improved control approach by applying a feedforward pitch angle adjustment decreases the risk of overspeed situations [31]. The influence of SI provision by wind turbines on its energy yield and thus its costs for the provision are neglectable [32]. The energy yield loss is quantified to be 0.3 % [30]. It can be decreased further by improved control algorithms [31].

A general introduction to SI provision using energy storage systems in stand-alone or hybrid applications is given by Ayamolowo et al. [25]. Therefore, the control approach of a virtual synchronous machine is applied to mimic the behaviour of a synchronously connected rotating mass. A comprehensive review of different control algorithms to provide SI with frequency converter-connected units is provided by Tamrakar et al. [33]. The response times of energy storage units providing SI and thus, exchanging energy with the power system, depend on the technology [23]. Lithium-based batteries, flow batteries and super capacitors have a response time ranging from 10 to 20 ms. Lead-acid batteries have a response time of about 40 ms. Since a wrong approach in calculating the ROCOF can lead to incorrect responses from units providing SI [34], the European Network of Transmission System Operators for Electricity (ENTSO-E) recommends a sliding window of 500 ms to determine the ROCOF [35]. Hence, units providing SI cannot substitute synchronously connected rotating masses and their inherent inertia response [2, 24].

Since power system inertia is decreasing due to decarbonisation efforts and the integration of frequency converter connected RES, inertia in future power systems has to be measured. Power system estimation methods can be classified into time horizon methods such as offline post-mortem methods, discrete online methods, continuous online methods or forecasting methods, as well as classified into methods covering different spatial approaches such as system-wide methods, zonal methods, nodal methods or embedded generation methods [36]. The stored kinetic energy in the Nordic synchronous area has been estimated by applying an online zonal approach during six events taking place between June 2017 and September 2017 by the Nordics Transmission System Operators (TSOs) [37]. The stored kinetic energy in the Nordic system ranges from 145 GWs to 179 GWs. During the tuning phase of the estimation method, the stored kinetic energy ranged from 210 to 265 GWs. System load during this phase ranged from 37.3 up to 48.8 GW leading to a system inertia constant between 5.66 to 6.11 s. The ENTSO-E applied a post-process approach to the market modelling outcome for their inertia study [38]. With respect to the analysed scenarios for the years 2030 and 2040, the inertia constant of Continental Europe varies between 1.1 to 4 s [39]. It is concluded that, in Continental Europe, the reduction of inertia is noticeable [39].

Currently, many grid-connected devices and machines have a maximum ROCOF threshold [36]. Most ROCOF relays have a threshold of 1 Hz/s to withstand before disconnecting from the power system [40]. This withstand capability of 1 Hz/s is also specified by the ENTSO-E and a withstand capability of 3 Hz/s is recommended for future systems as well as a potential imbalance ratio of 40 % [41]. Thus, rotating masses are an indispensable part of power systems, and a minimum inertia level has to be specified [24]. This level of inertia is also referred to as critical inertia [42]. Critical inertia is the minimum level of synchronous inertia necessary to provide grid frequency response reserves with sufficient time to be deployed and prevent the first stage of load shedding [42]. If minimum standards for system inertia are not specified in power systems, this will lead to substantial additional costs to power markets [43].

The paragraphs above review publications considering technical aspects of system inertia. However, it is also indicated that insufficient system inertia and units providing an inertia response result in overall economic losses [2, 24, 43]. Inertia provision can either be realised through law or commercialisation [44]. Synchronous inertia is currently treated as a free-of-charge source [24]. It is a by-product of units connected synchronously to the power system. As the share of frequency converter connected RES and storage units increase, inertia requirements and services will become a valuable commodity and providing units of such services will demand financial compensation [33]. Market design for the commodity inertia is still an open research area [45]. A market-based solution is considered to be the cost-efficient solution [45]. Therefore, ancillary service markets are reviewed to distinguish between separate services and to prepare for commercialisation [24]. A proper market framework for inertia response services does yet not exist [23].

In conclusion, the reviewed literature highlights the economic value of power system inertia for grid frequency stability. Since the penetration of frequency converter connected RES and storage units increase, power system inertia decreases. Although the behaviour of a synchronously connected rotating mass can be emulated in the form of SI, it is not a direct substitution of an inherent instantaneous inertia response. Hence, in order to maintain controllability of the grid frequency, system operators have to define critical inertia levels. As inertia is becoming a scarce commodity, units providing an inertia response demand financial compensation for their service. New markets for such inertia services are likely the most cost-efficient solution. In total, it can be concluded that inertia provision in future power systems is associated with costs and that inertia has an economic value.

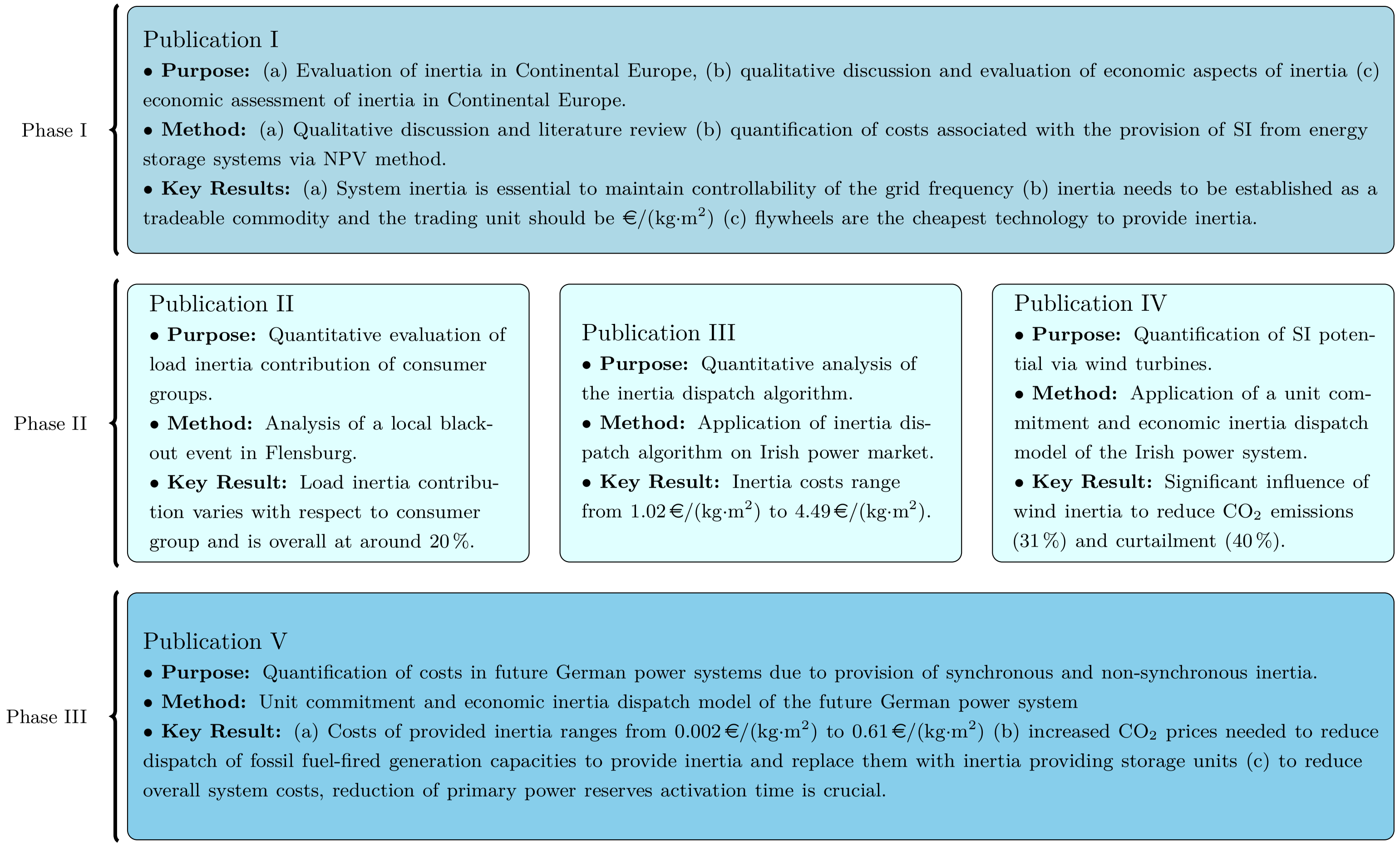
3 Research Overview and Summary

The publications part of the cumulative dissertation at hand can be categorised into three research phases. Figure 3.1 provides an overview of the research phases and how the five publications are categorised. Each block within the figure represents a single publication. The purpose, methodical approach and key results of each publication are summarised per block.

Phase I The first publication of this thesis forms the foundation and thus marks the first phase of the research [46]. Taking the synchronous area of Continental Europe, fundamentals about decreasing power system inertia are introduced and basic economic aspects are discussed. A trading unit for system inertia in future power systems is discussed and defined. A future solution is financially evaluated in which energy storage systems are applied to provide SI.

Phase II The second phase of the work comprises Publications II to IV and single issues related to inertia in power systems are presented. Publication II analyses the demand side contribution of synchronous inertia focusing on the categorisation of consumers into groups of consumers and their respective inertia contribution [47]. Publication III evaluates an energy marginal cost based market approach to secure sufficient inertia via an extension of the current dispatch methodology of the day-ahead power market [48]. Therefore, empirical data from the all-Island Irish power market are applied in a developed day-ahead market model to match supply and demand and, at the same time, secure sufficient system inertia. Publication IV evaluates and assesses the beneficial influence of SI provided by wind turbines on CO_2 emissions, RES-curtailment and systems costs via an open-source unit commitment and economic inertia dispatch model of the 2040 Irish power system [49].

Phase III Publication V combines the findings of the previous publications and evaluates the costs which can be associated with the provision of synchronous and non-synchronous inertia in the future German power system [50]. For this purpose, an open-source unit commitment and economic inertia dispatch model of the future German system is created and optimised. Finally, costs for the provided inertia are determined.



Phase I

Publication I

- **Purpose:** (a) Evaluation of inertia in Continental Europe, (b) qualitative discussion and evaluation of economic aspects of inertia (c) economic assessment of inertia in Continental Europe.
- **Method:** (a) Qualitative discussion and literature review (b) quantification of costs associated with the provision of SI from energy storage systems via NPV method.
- **Key Results:** (a) System inertia is essential to maintain controllability of the grid frequency (b) inertia needs to be established as a tradeable commodity and the trading unit should be €/(kg·m^2) (c) flywheels are the cheapest technology to provide inertia.

Phase II

Publication II

- **Purpose:** Quantitative evaluation of load inertia contribution of consumer groups.
- **Method:** Analysis of a local blackout event in Flensburg.
- **Key Result:** Load inertia contribution varies with respect to consumer group and is overall at around 20 %.

Publication III

- **Purpose:** Quantitative analysis of the inertia dispatch algorithm.
- **Method:** Application of inertia dispatch algorithm on Irish power market.
- **Key Result:** Inertia costs range from 1.02 €/(kg·m^2) to 4.49 €/(kg·m^2).

Publication IV

- **Purpose:** Quantification of SI potential via wind turbines.
- **Method:** Application of a unit commitment and economic inertia dispatch model of the Irish power system.
- **Key Result:** Significant influence of wind inertia to reduce CO_2 emissions (31 %) and curtailment (40 %).

Phase III

Publication V

- **Purpose:** Quantification of costs in future German power systems due to provision of synchronous and non-synchronous inertia.
- **Method:** Unit commitment and economic inertia dispatch model of the future German power system
- **Key Result:** (a) Costs of provided inertia ranges from 0.002 €/(kg·m^2) to 0.61 €/(kg·m^2) (b) increased CO_2 prices needed to reduce dispatch of fossil fuel-fired generation capacities to provide inertia and replace them with inertia providing storage units (c) to reduce overall system costs, reduction of primary power reserves activation time is crucial.

Figure 3.1: Overview of publications and research phases of the dissertation.

3.1 Research Phase I - Publication I

In order to decarbonise the Continental European energy system, RES are integrated into the power system and fossil fuel-fired power plants are displaced. Since most integrated RES are frequency converter connected units such as wind turbines and photovoltaic systems, power system inertia decreases. So far, synchronous inertia is a free-of-charge by-product provided by synchronously connected rotating masses, mostly provided by synchronously connected generators. Units dispatched to provide synchronous inertia or SI will demand financial compensation for their grid service. Hence, a physical unit needs to be assigned to the commodity inertia. The appropriate trading unit is assigned to the service inertia with regard to its physical functionality within the power system.

Power system inertia is needed; first, to limit the ROCOF and second, to limit the grid frequency nadir or peak in combination with other ancillary services such as primary grid frequency control reserve. Since the grid frequency is not constant, inertia is constantly activated. The power provided by synchronously connected rotating masses is determined by the grid frequency, f_{grid}, the ROCOF, $\delta f_{grid}/\delta t$ and the unit's moment of inertia J_i as depicted via Equation (3.1).

$$P_{i,inertia} = J_i \cdot 4 \cdot \pi^2 \cdot f_{grid} \cdot \frac{\delta f_{grid}}{\delta t} \tag{3.1}$$

The integral of Equation (3.1) determines the exchanged energy with the grid via the inertia response considering the grid frequency at the beginning of an event, $f_{grid,1}$ and at the end of an event $f_{grid,2}$. This is depicted in Equation (3.2).

$$E_{inertia} = \frac{1}{2} \cdot J \cdot 4 \cdot \pi^2 \cdot (f_{grid,1}^2 - f_{grid,2}^2) \tag{3.2}$$

Due to its nature and functionality, the appropriate trading unit for inertia is Euros per moment of inertia (€/(kg·m^2)). Of course, the currency is not fixed and, in this case, is related to the example region of Continental Europe. In contrast to grid frequency ancillary services, usual trading units are €/MW for power and €/MWh for energy. However, in the case of the inertia response, provided power and exchanged energy are linked via the unit's moment of inertia. The grid frequency and ROCOF are exogenously specified and can be assumed to be constant for this consideration. Hence, the trading unit for inertia is Euros for the provided moment of inertia (€/(kg·m^2)).

Inertia in the future Continental European power system comprises a synchronous inertia part needed to limit the instantaneous ROCOF and a non-synchronous part which in combination with the synchronous part is needed to limit the grid frequency nadir or peak. It is assumed in the first publication, that the synchronous inertia share is always provided by synchronously connected hydro and biomass power plants. In the first publication, this share of inertia is referred to as the residual inertia, J_{res}. Economically assessed is thus only provided SI. Although an obvious solution for the provision of SI would be wind turbines, it is not incorporated at this stage of the research, since the impact of SI on the wind turbines loads due to the applied control approach was not yet assessed. Therefore, only SI provision by three types of battery storage units, supercapacitors and non-synchronous flywheel storage systems are considered and economically assessed.

A grid frequency model which depicts the inertia response from synchronously connected rotating masses and the provision of primary power reserve with characteristics defined by the ENTSO-E is applied to determine the overall required system inertia [5]. The reference incident, i.e., the loss of 3 GW of power generation, is modelled and the required moment of inertia is adapted to limit the grid frequency nadir to 49 Hz. Thus, disconnection of loads is avoided. Overall, a system-wide moment of inertia of $3.11 \cdot 10^6\,\mathrm{kg \cdot m^2}$ is required to stabilise the grid frequency with regard to current specifications.

Although the moment of inertia is the previously determined trading unit, a translation for power and energy is required to dimension the storage system providing SI. Considering the current thresholds for the ROCOF and the grid frequency, the overall system moment of inertia translates to a required power of 12.65 GW and a required energy of 6.75 MWh, applying and rearranging Equations (3.1) and (3.2) for power and energy respectively. The considered storage units are Lead-Acid, Lithium-Ion and Sodium Sulphur battery storage units as well as supercapacitors and non-synchronous flywheels. The considered energy storage types have the technical capabilities to provide a very fast response as required for the application of SI provision. A spatial distribution of the storage units is not analysed, but it is proposed to follow the principle of joint action in the same way as to the spatial distribution of units providing primary reserve in Continental Europe per control block [5].

Table 3.1 provides an overview of the results of the economic assessment. The Net Present Value (NPV) method is applied for the financial assessment. It is important to highlight that the NPV results depicted in Table 3.1 represent discounted negative cash flow. Investment costs as well as costs for Operation and Maintenance (O&M) and

Table 3.1: Result overview of the assessed storage units of Publication I.

Parameter	Unit	Storage type				
		Lead Acid	Lithium Ion	Sodium Sulphur	Super Capacitor	Non-sync. Flywheel
NPV	bn €	11.79	8.82	10.61	8.24	7.19
LCOI	€/(kg·m^2·year)	275.22	205.64	247.48	192.12	167.64

costs of capital are discounted over a fixed period of time. Hence, the least cost solution is likely the one to be applied since it induces the fewest costs on the power system to maintain controllability of the grid frequency.

Depicted in Table 3.1 as well, are the Levelised Costs of Inertia (LCOI). Following the approach to determine the levelised costs of energy, the LCOI are determined. The LCOI is a measure of the overall lifetime net present costs of a storage system with respect to the annually provided inertia.

Within the research scope of the first publication, the results indicate that the application of non-synchronous flywheel systems is the least-cost solution to provide the overall required SI with LCOI of 167.64 €/(kg·m^2) per year. However, a mix of different sources to provide synchronous inertia and SI will determine the most costs-efficient, system-wide solution mix in future power systems.

3.2 Research Phase II

The second research phase consists of publications II to IV and answers individual questions related to inertia in power systems such as load inertia contribution, an economical assessment of inertia provision via the day-ahead energy market and the beneficial influence of SI provided by wind turbines on the future power system with regards to CO_2 emission, RES curtailment and system costs.

3.2.1 Publication II

Power system inertia is not only provided by synchronously connected generators but also by synchronously connected rotating masses from power consumers. A literature review has further revealed that knowledge about inertia provided by power consumers is limited to system-wide load inertia contribution. Further details, such as the contribution of different consumer groups are not known. An incident on 09 January 2019 in a transmission line connecting the local Flensburg power system with the power system of Denmark occurred. Load shedding in the local power system was necessary in order to re-establish power balance. Data provided by the local energy supplier allowed for an in-depth assessment of the load inertia contribution.

On 09 January 2019 a short circuit in a transmission line from the local Flensburg power system to Denmark occurred. First, it resulted in the disconnection of the transmission line itself. Second, a large gas turbine of the local energy supplier tripped. A connection of the local Flensburg power system to the surrounding power system of Schleswig-Holstein was not possible. Hence, the Flensburg power system actually had to be operated as a grid island. Limited power generation capacities and increasing demand in the morning hours resulted in a large power imbalance and in order to stabilise the grid frequency, the energy supplier gradually disconnected several city districts. At the end of the events, almost the whole city was affected by the load disconnection.

In collaborative work, the local energy supplier allowed for deep insight into the events and provided large sets of data such as power generation data per connected generation unit, power demand data for various measurement points of the local power system as well as a grid frequency measurement series. Furthermore, data about the provided inertia for each connected generator is available. Table 3.2 provides an overview of the events with information about the time, the location, a description of the event, the resulting power imbalance, the grid frequency and the ROCOF.

As visible via Table 3.2, different districts of Flensburg have been disconnected from the grid, thus marking an event. Disconnected districts are categorised with regard to the dominating type of power consumers. Overall, four consumer categories are introduced: the group of private households, retail businesses, an industry-based group and a mixed group covering trade and commerce businesses as well as industry businesses.

As introduced in Section 2.4, current power system inertia, J_{sys} is the sum of the provided inertia from synchronously connected generators, J_i and from synchronously connected loads, J_{load}. Hence, substituting J_{sys} with $\sum J_i + J_{load}$ in Equation (2.1) and rearranging the equation for J_{load} results in a quantification of the system load inertia contribution.

Table 3.2: Overview of Publication II input data. List of events, time of occurrence, event description, power imbalance, grid frequency and the ROCOF of the Flensburg blackout.

ID	Time	Location of event	Description of Event	ΔP [MW]	f_{grid} [Hz]	ROCOF [Hz/s]
Ev1	06:18:54	Grid line DK	Short circuit	48.58	49.82	0.591
Ev2	06:30:32	TS-Ost	Stepwise load shedding	4.06	49.12	0.3653
Ev3	06:38:11	TS-Ost	Stepwise load shedding	3.8	48.2	0.3695
Ev4	07:00:09	TS-Ost	Full load shedding	4.38	48.41	0.4391
Ev5	07:15:19	TS-Karlstr.	Full load shedding	7.9	49.17	0.782
Ev6	07:16:49	TS-Peelwatt	Full load shedding	9.45	48.83	0.9381
Ev7	07:18:10	TS-Nord	Stepwise load shedding	6.36	49.9	0.6425
Ev8	07:18:54	TS-Nord	Stepwise load shedding	9.24	49.93	0.9744
Ev9	07:25:59	TS-Süd	Full load shedding	10.24	48.54	2.18

Assuming that load inertia contribution is constant between the events, the load inertia contribution for each district is the difference of $J_{load,n} - J_{load,n-1}$.

Table 3.3 shows the calculated moments of inertia and Table 3.4 the corresponding stored kinetic energies.

Table 3.3: Overview of the calculated moment of inertia J_{sys}, J_{load} and $J_{load,district}$.

ID	J_{sys} [kg·m^2]	J_{load} [kg·m^2]	$J_{load,district}$ [kg·m^2]	Disconnected district
Ev1	-	-	-	-
Ev2	5731.37	1215.70	-	TS-Ost
Ev3	5404.59	888.91	326.78	TS-Ost
Ev4	5219.34	703.67	185.24	TS-Ost
Ev5	5204.28	688.61	15.07	TS-Karlstr
Ev6	5120.73	605.06	83.54	TS-Peelwatt
Ev7	5024.86	509.19	95.88	TS-Nord
Ev8	4810.76	295.09	214.10	TS-Nord
Ev9	2451.23	158.28	136.81	TS-Süd
-	-	-	158.28	TS-HKW

The load inertia contribution can be expressed via the inertia constant (see Equation 2.4) as well. Figure 3.2 illustrates provided average inertia constants for each consumer category via a bar plot. The range of the inertia constants for each power consumer category is indicated via the whiskers.

Table 3.4: Tabular list of calculated stored kinetic energy.

ID	$E_{kin,sys}$ [MWs]	$E_{kin,load}$ [MWs]	$E_{kin,load,district}$ [MWs]	Disconnected district
Ev1	-	-	-	
Ev2	282.83	59.99	-	TS-Ost
Ev3	266.71	43.87	16.13	TS-Ost
Ev4	257.56	34.72	9.14	TS-Ost
Ev5	256.82	33,98	0.74	TS-Karlstr
Ev6	252.70	29.86	4.12	TS-Peelwatt
Ev7	247.97	25.13	4.73	TS-Nord
Ev8	237.40	14.56	10.57	TS-Nord
Ev9	120.96	7.81	6.75	TS-Süd
-	-	-	7.81	TS-HKW

Overall, the system load inertia contribution of the research coincides with the literature findings. Differences are small and can be explained by the size of the researched system. The inertia constant result range of the category **private households** is large. The naval military base of Mürwick is connected to the district TS-Ost and it is concluded that its inertia contribution is significant due to large synchronously rotating masses and thus explaining the wide result range. Due to early time of the day, the inertia contribution of the categories **retail businesses**, **industry businesses and trade and commerce businesses** as well as **industry businesses** is small. At the time of the events, those businesses were outside their business hours. Further, two large industry businesses which are closely located to the local energy supplier in Flensburg, a vehicle construction company and a shipyard, remained connected. Thus, its influence could not be assessed.

Due to the timing of the researched events, results have their limitations, but the work is still valuable. Insights from this work can be applied by grid operators to optimise disconnection sequences. Grid operators are able to quantify the lost load inertia and can thus disconnect parts of the grid in a target-orientated manner to stabilise the grid frequency and at the same time limit impact on power consumers.

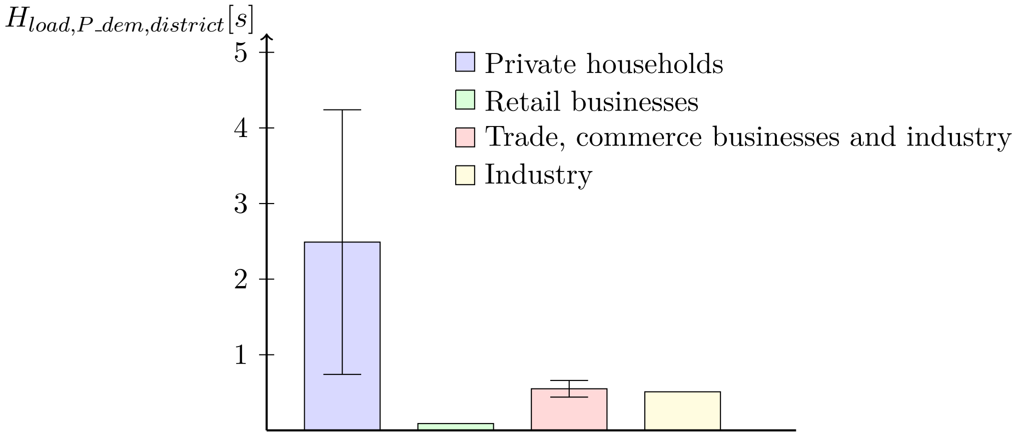


Figure 3.2: Illustration of the calculated results of $H_{load,P\_dem,district}$. Each depicted bar shows the inertia provided by the particular consumer category. The coloured bar indicates the average inertia constant and the whiskers the absolute range of results.

3.2.2 Publication III

A dispatch methodology to secure sufficient power system inertia via the day-ahead energy market is assessed in the third publication. The methodology determines the lowest day-ahead market dispatch solution while ensuring sufficient power system inertia to maintain the controllability of the grid frequency. Inertia dispatched via the algorithm can be economically quantified.

The inertia dispatch methodology is a supplementary algorithm to the day-ahead energy market functionality in which supply and demand are matched [51]. It is assumed that the grid operator has perfect knowledge about provided inertia from power generators. Hence, the power system inertia provided as a result of the day-ahead market dispatch after matching supply and demand bids can be calculated. In case the power system inertia is below the system's minimum inertia constraint after balancing generation and demand, the merit order is restructured. The most expensive, in terms of marginal energy costs, non-inertia-providing generation unit is replaced with the next-in-line cost-intensive inertia-providing unit in the merit order. This iteration is repeated until the system is provided with sufficient inertia. Hence, system inertia constraints are taken into account via a market process prior to real-time physical delivery. Figure 3.3 depicts the schematic application of the dispatch algorithm and the resulting shift of the supply bid curve due to the replacement of non-inertia-providing units. Further, additional costs due to the application of the algorithm can be allocated to the additionally provided inertia. The inertia dispatch algorithm includes synchronous inertia and SI provided by wind turbines. The continuous SI provision via wind turbines is incorporated into the model [30].

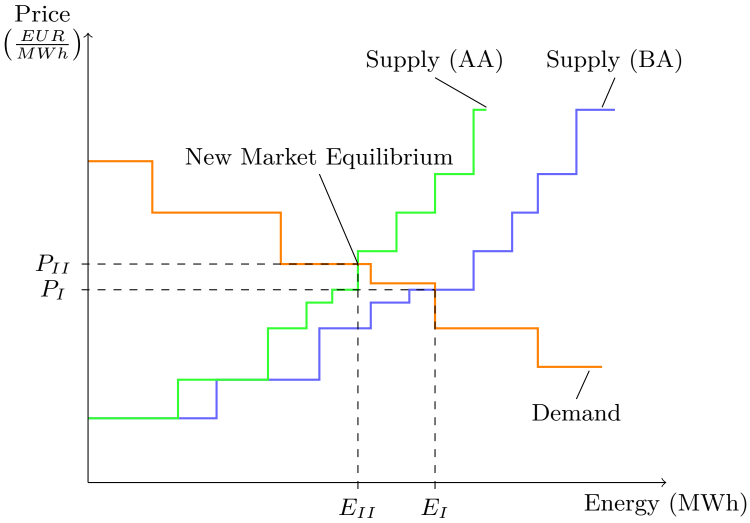


Figure 3.3: Intersection of the supply (blue) and demand (orange) bids before application (BA) of the inertia dispatch algorithm, and the demand bids (green) after application (AA) of the inertia dispatch algorithm. Due to the application of the algorithm, the market equilibrium shifts from (P_I/E_I) to (P_{II}/E_{II}).

The methodology is applied with empirical data from the all-Island Irish power system. A six-month period from 06 March 2020 to 21 September 2020 is analysed. Additionally, data provided by the ENTSO-E is applied as well, to account for power generation not traded via the day-ahead market but via bilaterally organised trades. Thus, inertia provided by such units is incorporated into the overall analysis. Overall, eight scenarios are analysed covering different assumptions of the inertia constant for different types of generators, the system inertia constraint as well as whether SI is provided by wind turbines. The logic of the methodology is implemented into an open-source algorithm written in Python programming language [52].

With respect to the combination of scenario parameters, the number of times in which no solution was found by the inertia dispatch algorithm varies significantly. No solution, in this case, means that no equilibrium of power generation bids and demand bids is found to meet the minimum inertia constraint as well. In such cases, insufficient overall inertia is provided by units offering a bid to the market. Results clearly indicate that the assumption for the synchronously connected generator's inertia constant has a very

Table 3.5: Results of the applied inertia dispatch methodology of Publication III. Depicted are the number of times the algorithm is executed and the number of times without finding an equilibrium between supply and demand.

Scenario	No. of methodology application	Runs w/o solution
$E_{kin,dem} = 23\,\text{GWs}$, H_{high}, non-SI	789	38
$E_{kin,dem} = 23\,\text{GWs}$, H_{high}, SI	507	5
$E_{kin,dem} = 18.4\,\text{GWs}$, H_{high}, non-SI	306	0
$E_{kin,dem} = 18.4\,\text{GWs}$, H_{high}, SI	133	0
$E_{kin,dem} = 23\,\text{GWs}$, H_{low}, non-SI	4683	4129
$E_{kin,dem} = 23\,\text{GWs}$, H_{low}, SI	4573	3591
$E_{kin,dem} = 18.4\,\text{GWs}$, H_{low}, non-SI	3163	1358
$E_{kin,dem} = 18.4\,\text{GWs}$, H_{low}, SI	2547	896

high influence on the number of times in which the inertia dispatch algorithm is applied. With the application of the lower bound of assumed inertia constants (H_{low}), the number of times the algorithm is applied increases. The number of times in which the algorithm resulted in no found solution also increases significantly. The positive influence of a lower system inertia constraint due to the depiction of load inertia ($E_{kin,dem} = 18.4\,\text{GWs}$) is also visible. Comparing equal scenario parameter combinations, in terms of the system inertia constraint as well as for the inertia constant assumption, shows that SI provision by wind turbines reduces the number of times the inertia dispatch algorithm itself has to be applied and also the number of times no solution found. The costs of the additionally provided inertia for the six-month period range from 1.02 €/(kg·m^2) to 4.49 €/(kg·m^2).

The results indicate that the inertia dispatch algorithm underestimates the available inertia. Thus, the number of times in which the methodology has to be applied is too high. Furthermore, the number of times in which the algorithm results in no equilibrium between power demand and power consumption is too high as well. This is likely due to inaccurate data. Power generation units which are only operated for self-consumer balancing are connected to the power system as well but no trades via a market are executed. Hence, they do also provide inertia, but are not listed via the available data sources.

Furthermore, such an algorithm would likely change the bidding strategies of power generation units. Hence, more units providing inertia and especially a large moment of

Table 3.6: Results of the applied inertia dispatch methodology of Publication III. Depicted are additional system costs, additionally provided inertia as well as costs for provided additional inertia.

Scenario	Add. system costs [M€]	Add. inertia [kg·m^2]	Costs for inertia [€/(kg·m^2)]
$E_{kin,dem} = 23\,\text{GWs}$, H_{high}, non-SI	362	80,723,365	4.49
$E_{kin,dem} = 23\,\text{GWs}$, H_{high}, SI	191	48,174,204	3.98
$E_{kin,dem} = 18.4\,\text{GWs}$, H_{high}, non-SI	49	28,809,714	1.7
$E_{kin,dem} = 18.4\,\text{GWs}$, H_{high}, SI	13	12,931,785	1.02
$E_{kin,dem} = 23\,\text{GWs}$, H_{low}, non-SI	-	-	-
$E_{kin,dem} = 23\,\text{GWs}$, H_{low}, SI	-	-	-
$E_{kin,dem} = 18.4\,\text{GWs}$, H_{low}, non-SI	-	-	-
$E_{kin,dem} = 18.4\,\text{GWs}$, H_{low}, SI	-	-	-

inertia would likely bid differently assuming its bid is being awarded due to a potential application of the inertia dispatch algorithm in times of a low-inertia system.

In general, the inertia dispatch algorithm is applicable and results in balancing power generation bids and demand bids and at the same time secures sufficient power system inertia. However, as shown by the results and discussion above, it has its limitations. Furthermore, its biggest weakness is increased CO_2 emissions due to the application of the algorithm. Due to its design of replacing non-inertia-providing units with inertia-providing units, likely RES are being replaced by fossil fuel-fired power plants. Also, the application of such an algorithm could potentially lead to a re-activation of decommissioned carbon dioxide emission-intensive old power plants due to potential new revenue streams. Increased CO_2 emissions prices could counteract such an undesired development. Hence, less CO_2 emitting units like gas turbines are favoured as opposed to e.g., coal-fired power generation units. Considering increased CO_2 emissions prices could thus enable the application of the inertia dispatch methodology during transition phases until a market for inertia itself is established.

3.2.3 Publication IV

Energy system modelling is a method used in a variety of projects to answer different research questions [53]. Modelling future scenarios of power system inertia, however, is a topic which is rarely focused on in unit commitment and economic dispatch modelling. Especially when systems with a high share of non-synchronous penetration are considered. If considered at all, only synchronous inertia is depicted. SI as a grid service is not yet considered in unit commitment and economic dispatch models, although the beneficial influence is acknowledged. The fourth publication closes this research gap by creating an unit commitment and economic inertia dispatch model incorporating SI as a dispatchable grid service. The potential and influence of SI provided by wind turbines on system parameters such as CO_2 emissions, RES curtailment and system costs are analysed. As in Publication III, the logic of the continuous wind inertia controller is incorporated into the unit commitment and economic inertia dispatch model.

Scenarios of the 2040 Irish power system are used for the research. The scenarios are based on the 2020 Ten-Years Network Development Plan of the ENTSO-E. The open-source modelling framework Open Inertia Modelling (OpInMod) is used to build the Irish power system model. OpInMod optimises toward the least cost dispatch solution while balancing power demand and supply and meeting minimum inertia constraints. Overall required system inertia is defined by the Irish grid operator [13]. The critical level of synchronous inertia is defined by the maximum permissible ROCOF and the Irish reference incident, i.e., the loss of the transmission line between the Irish and the British power system. A base scenario is optimised without SI provision from wind turbines. Only synchronous inertia is provided by synchronously connected power generation units. This is the reference scenario, which all other scenarios are compared with.

Results indicate that due to the intermittent nature of wind turbines prime mover, SI provision is limited. Additionally, the continuous wind inertia controller is only able to provide a synthetic inertia response for a rotational speed above 0.67 pu. In total, for about 4,300 hours of the modelled time frame and scenarios, no SI is provided by wind turbines at all. Nevertheless, the beneficial influence of SI provided by wind turbines is substantial as depicted in Table 3.7.

With respect to the scenario parameter combination of the ROCOF threshold, which determines the synchronous critical inertia level, and the demanded system inertia constant which the continuous wind inertia controller is demanded to replicate, up to 30.99 % of CO_2 emissions can be saved. With respect to the base scenario, at least 14.7 % of CO_2 emissions can be saved.

Table 3.7: CO_2 emissions and curtailment results of the analysed scenarios of Publication IV.

Scenario	CO_2 Emissions [t]	Reduction[a] [%]	Curtailment [MWh]	Reduction[a] [%]
Base	4,789,225	0.00	2,613,969	0.00
ROCOF = 1 Hz/s, H_{dem} = 3.5 s	4,085,047	14.70	2,341,29	10.43
ROCOF = 1 Hz/s, H_{dem} = 5 s	4,066,117	15.10	2,341,290	10.43
ROCOF = 2 Hz/s, H_{dem} = 3.5 s	3,474,372	27.45	1,575,412	39.73
ROCOF = 2 Hz/s, H_{dem} = 5 s	3,305,005	30.99	1,570,872	39.90

[a] with respect to the base scenario.

A similar development can be observed in terms of curtailed RES feed-in. Curtailed RES energy can be reduced by at least 10.43 % and up to 39.90 %.

System cost-saving potential due to the provision of SI by wind turbines is also high as visible in Table 3.8. Cost savings range from 15.12 % up to 32.72 %. Again, increasing the inertia constant wind turbines are demanded to emulate, while decreasing the overall critical level of inertia, increases costs savings significantly. Decreasing the critical overall inertia level by allowing a higher permissible ROCOF increases cost savings significantly from at least 15.12 % up to at least 28.71 %. Expressing cost saving potential per provided additional SI ranges from 0.06 €/(kg·m^2) to 0.17 €/(kg·m^2). When increasing the inertia constant to be emulated by wind turbines while keeping the ROCOF threshold constant, cost savings per provided SI are less significant. Nevertheless, SI provision by wind turbines has a limited impact on the wind turbines energy yield. Thus, the provided SI should be maximised.

3.3 Research Phase III - Publication V

The last publication of this thesis marks the third research phase of the dissertation project. System costs of future German power systems with a focus on costs associated with the provision of inertia are assessed. In contrast to Publication IV, inertia provision via storage units is also considered in order to reduce must-run capacities. Only system

Table 3.8: Overall system costs and cost savings with respect to the provided SI of the analysed scenarios.

Scenario	System Costs [€]	Reduction[a] [%]	Cost Savings[a] for provided SI [€/(kg·m^2)]
Base	737,265,818	0.00	0.00
ROCOF = 1 Hz/s, H_{dem} = 3.5 s	625,765,315	15.12	0.09
ROCOF = 1 Hz/s, H_{dem} = 5 s	622,733,455	15.53	0.06
ROCOF = 2 Hz/s, H_{dem} = 3.5 s	525,560,884	28.71	0.17
ROCOF = 2 Hz/s, H_{dem} = 5 s	496,034,635	32.72	0.14

[a] with respect to the base scenario.

costs of the German power system are considered and analysed. It is assumed that, likewise to primary control reserves, the principle of joint action is applied and every control block within the Continental European power system provides a share of system inertia necessary to maintain controllability of the grid frequency.

As already proven to be effective, OpInMod is applied to build a model of the German power system. Neighbouring countries are modelled as well to depict imported and exported energy. Dispatchable inertia units are synchronously connected generators from thermal power plants and hydropower plants, synchronously connected storage units, wind turbines and battery storage units. Newly incorporated into OpInMod is an investment part. Hence, OpInMod optimises towards the least-cost solution of dispatch related costs as well as investment costs, if required.

Three scenario families are analysed, of which two scenarios (Distributed Energy and National Trends) are based on the 2020 Ten-Years Network Development Plan and reflect the year 2040, and one scenario (RE100) is based on the 100 % RES scenario of the e-Highway 2050 study of the ENTSO-E. Figure 3.4 provides an overview of the installed capacities of each scenario. Two parameters are varied to determine the total needed system synchronous inertia and the required overall system inertia. The ROCOF threshold, which determines the critical synchronous inertia level and the activation time of primary response reserves. Faster activation time results in less required system inertia before the grid frequency nadir is reached. As with Publication I, a simple grid

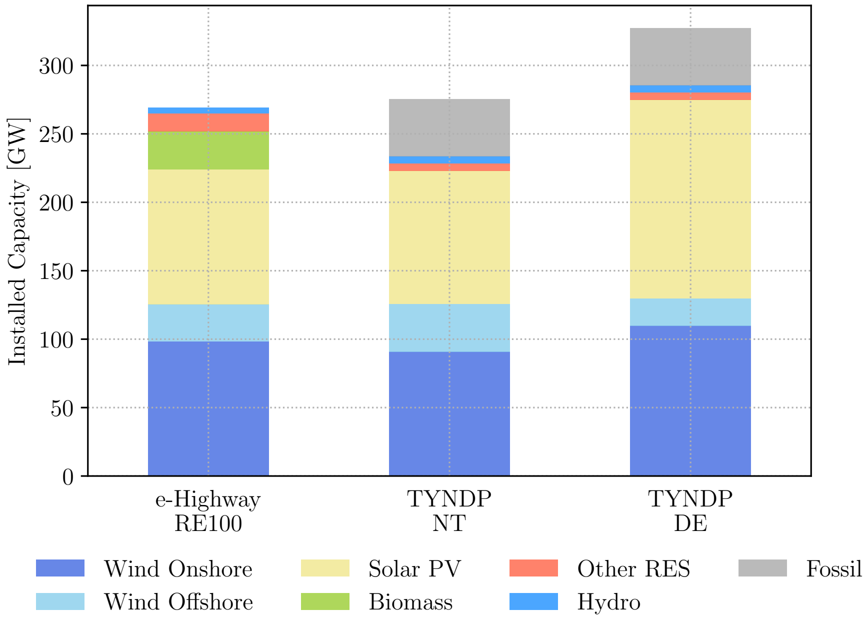


Figure 3.4: Overview of installed capacities per scenario and generation type.

frequency model is used to determine the overall needed system inertia. This time, the power imbalance is determined by the loss of the largest transmission line as concluded by the ENTSO-E for future scenarios as well. Furthermore, the self-regulation effect of loads is incorporated. Parameter combinations of the maximum allowable ROCOF and the activation time are as follows:

1. a 1 Hz/s ROCOF threshold and an activation time of 30 s representing current system specifications in Continental Europe,
2. a 1 Hz/s ROCOF threshold and an activation time of 2 s which is the activation time of FFR and
3. a 2 Hz/s ROCOF threshold and an activation time of 2 s.

For each scenario family, a base scenario without inertia constraints is optimised to act as the foundation for the analysis. Combining the three scenario families, three-parameter combinations and the base scenario results in a total of twelve researched scenarios.

Table 3.9: Overview of the optimisation results per scenario and parameter.

Scenario	Parameter Combination	Share Non-Sync. Generation [%]	System Costs [bn €]	Costs per Inertia [€/(kg·m^2)]
National Trend	Base Scenario	80.05	4.513	0.00
	1 Hz/s, 30 s	79.58	17.546	0.44
	1 Hz/s, 2 s	79.23	5.158	0.04
	2 Hz/s, 2 s	79.36	4.655	0.01
Distributed Energy	Base Scenario	84.61	3.260	0.00
	1 Hz/s, 30 s	83.54	9.469	0.21
	1 Hz/s, 2 s	83.58	3.971	0.03
	2 Hz/s, 2 s	83.64	3.558	0.01
RE100	Base Scenario	77.55	6.589	0.00
	1 Hz/s, 30 s	77.30	31.925	0.61
	1 Hz/s, 2 s	77.61	6.640	0.003
	2 Hz/s, 2 s	76.93	6.610	0.002

The results of the optimised scenarios are shown in Table 3.9. In the National Trend scenario family, the share of non-synchronous penetration is around 79 %, in the Distributed Energy scenario family around 84 % and in the RE100 scenario around 77 %. Although the RE100 scenario represents a 100 % renewable scenario, non-synchronous penetration is lower compared to the Distributed Energy scenarios due to fewer installed capacities of wind turbines and photovoltaic systems.

Table 3.9 depicts an overview of the results of the researched scenarios and parameter combinations. The share of non-synchronous generation is highest in all scenarios in which inertia consideration is not part of the modelling process, i.e., in the base scenarios. When considering inertia depiction as part of the model, the share of non-synchronous generation decreases by up to 1.07 percentage points. Overall system costs are highest in each scenario with the 1 Hz/s, 30 s parameter combination. This is because of the investment in additionally needed synchronous condensers. Battery storage units, in this particular case Lithium-Ion battery storage units, are not additionally installed and dispatched due to investment optimisation decisions.

In the scenario family National Trends, inertia-related costs take up to 74.2 % of the overall system costs in the 1 Hz/s, 30 s parameter combination due to the investment in synchronous condensers. Up to 12.3 % in the 1 Hz/s, 2 s parameter combination and up to 3 % in the 2 Hz/s, 2 s parameter combination. In the Distributed Energy scenario, these numbers are 65.4 %, 17.7 % and 8.3 % respectively. In the RE100 scenario, the results are 79.3 %, 0.6 % and 0.3 % respectively. To limit the grid frequency nadir the highest demand for overall system inertia due to the 30 s activation time of primary reserves leads to the highest system costs because of the investment in synchronous condensers. The remaining system cost drivers are total natural gas costs in the National Trends and Distributed Energy scenario and biomass-related total costs in the RE100 scenario.

Comparing the scenario families and equal parameter combinations, the RE100 scenario family stands out with the highest system costs up to bn 31.9 €. The Distributed Energy scenario family is the one with the lowest system costs. Comparing the Distributed Energy and the National Trends scenarios, it can be concluded that higher installed capacities of non-synchronous generation units, i.e., wind turbines and photovoltaic systems, result in higher penetration shares and thus lower system costs due to less needed dispatchable marginal costs driven generation units, i.e., gas-fired power plants. Within each scenario family, the parameter combination of a 2 Hz/s ROCOF threshold and an activation time of 2 s leads to the lowest system cost increase with respect to the base scenario.

Overall system costs for additionally provided inertia range from 0.002 €/(kg·m^2) to 0.61 €/(kg·m^2). In the National Trend scenario family the system costs for additionally provided inertia range from 0.01 €/(kg·m^2) to 0.44 €/(kg·m^2), in the Distributed Energy scenario family from 0.01 €/(kg·m^2) to 0.21 €/(kg·m^2) and in the RE100 scenario family from 0.002 €/(kg·m^2) to 0.61 €/(kg·m^2).

Reduction of the primary reserve activation time decreases system costs significantly. However, as in the case of the National Trend scenario and the 1 Hz/s, 2 s parameter combination, it is less cost-intensive to dispatch CO_2 emitting thermal power plants than investing in additional synchronous condensers to match supply and demand and at the same time maintaining sufficient system inertia. An approach to address this undesired outcome is to increase costs for each emitted ton of CO_2. Costs for each ton of emitted CO_2 are increased stepwise from 75 €/t$_{CO_2}$ to 225 €/t$_{CO_2}$ by 25 €/t$_{CO_2}$ steps. Costs of 75 €/t$_{CO_2}$ for each emitted ton of CO_2 have been applied in the previously researched scenarios. Carbon dioxide emissions decrease with each incremental price increase down to 54.7 % with respect to the initial scenario. However, as a trade-off, system costs increase by 8.3 %. Increasing carbon dioxide emission costs above 225 €/t$_{CO_2}$ would not further decrease CO_2 emissions, since thermal units are needed to balance power.

The main analysis is conducted by applying the weather year 1982 which determines the dispatch of intermitted RES and filling level from hydro units due to hydro inflow variability. A sensitivity analysis of two more weather scenarios is conducted to analyse the influence of solar radiation and wind speed on photovoltaic and wind turbine feed-in as well as hydro inflow on dispatchable hydro units. Table 3.10 provides an overview of the analysed weather years and a qualitative declaration of the average impact of the respective source.

Results of the weather scenario sensitivity analysis for the three scenario families and the 1 Hz/s, 2 s parameter combination are depicted in Figure 3.5. Results indicate that the available wind potential has a high influence on the resulting system costs for the provided inertia. The weather year 1982 is the scenario with the lowest wind potential and results in the highest system costs. The weather year 2007 on the other hand is characterised by a high wind potential and thus results in the lowest system costs of the three analysed weather years.

Table 3.10: Overview of the applied weather years 1982, 1984 and 2007.

Weather Year	Demand	Wind	Solar	Hydro Inflow
1982	Medium	Low	High	Medium
1984	High	Medium	Low	Low
2007	Low	High	Medium	High

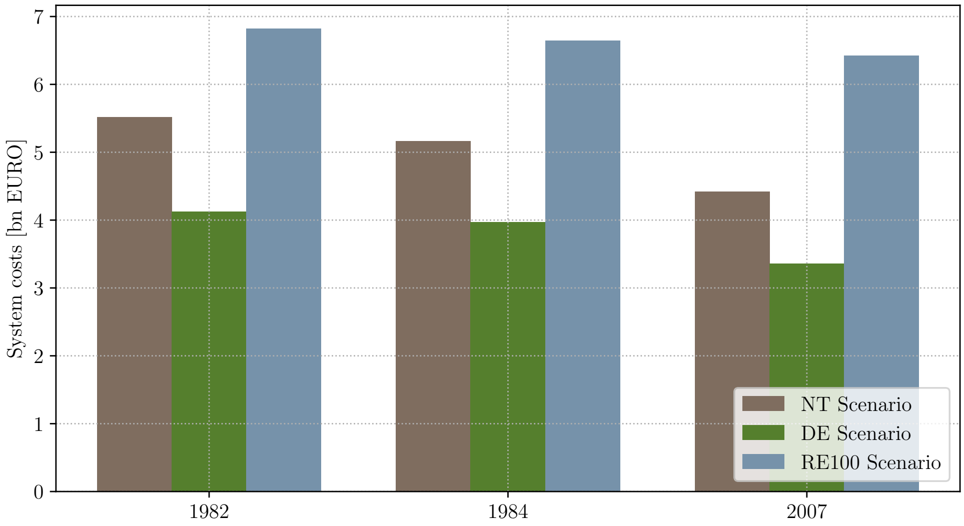


Figure 3.5: Illustration of the overall system costs with regard to the weather year input

4 Results, Discussion and Limitations

The aim of this thesis is to analyse and assess costs in future power systems associated with the provision of power system inertia. First, the above introduced sub-questions and the research question are answered. Thereafter, the results of the work and the individual publications with regard to referenced literature in Sections 1.1 and 2.4 are presented and discussed. Limitations of the presented findings are part of the discussion as well.

4.1 Results

First, the sub-questions as introduced in Section 1.2, are answered below.

1. What would be the appropriate unit to economically value costs for system inertia and thus be the trading unit for inertia in future power systems?

   Power system inertia's main purpose is first, to limit the ROCOF and second, to limit the grid frequency nadir or peak. To limit the ROCOF, synchronously connected rotating masses provide instantaneous power. To limit the grid frequency nadir or peak, energy is exchanged with the power system. Both provided power and exchanged energy are determined exogenously by the grid frequency and its time derivative, and endogenously by the unit's moment of inertia. Hence, from the unit itself, provided power and energy are determined from the unit's moment of inertia. The appropriate economic trading unit for system inertia is to take the physical functionality of inertia into account, and thus results in €/(kg·m^2).

2. Is it possible to further assess and evaluate the inertia contribution from power consumers?

   Synchronous inertia is provided by synchronously connected generators and synchronously connected rotating masses from power consumers. The overall inertia contribution from power consumers represents about 20 % of the total power system inertia. Four consumers categories are defined based on the dominating consumer group in the researched spatial area. The inertia contribution of private households is in the range of 0.7 to 4.2 s, for retail business it is 1 s, for industry business it is 0.5 s and for the mixed category of trade, commerce businesses and industry it is between 0.4 to 0.7 s.

3. Is Synthetic Inertia supplied by wind turbines able to provide a significant contribution to maintaining grid frequency stability?

   To determine the beneficial influence of wind inertia, quantifiable parameters are defined which for this purpose are CO_2 emissions, curtailed energy and system costs. Results of an all-island Irish power system model determine that SI provided by wind turbines can reduce CO_2 emissions by 30.99 %, curtailed energy by 39.9 % and system costs by 32.72 %. Hence, it can be concluded that the overall influence of wind inertia with regard to the chosen parameters is beneficial.

The main research question of this work can be answered as follows:

> *What are the costs associated with the provision of inertia in future power systems consisting of a high share of non-synchronous penetration?*
>
> Within the researched scenarios, the system costs, which are associated with the provision of inertia, range from 0.002 €/(kg·m^2) to 0.61 €/(kg·m^2). For the assessed National Trend scenarios, the share of non-synchronous penetration is between 79.25 % and 79.58 % and the costs of additional inertia are between 0.01 €/(kg·m^2) and 0.44 €/(kg·m^2). The share of non-synchronous penetration in the Distributed Energy scenarios ranges from 83.54 % to 83.64 % and the associated costs for inertia from 0.01 €/(kg·m^2) to 0.21 €/(kg·m^2). The share of non-synchronous penetration in scenario RE100 are between 76.93 % and 77.61 %, while additional inertia costs are between 0.002 €/(kg·m^2) and 0.61 €/(kg·m^2).

4.2 Discussion and Limitations

Throughout the whole thesis, energy system modelling is a methodological approach applied. Thus, in the first part of this section, aspects concerning the modelling approach such as the developed modelling tool itself, the depiction of SI and the assumed principle of joint action with regard to system inertia constraints are discussed. Thereafter, the results of the single publications are discussed, like resulting inertia costs, the determined trading unit of inertia, results of an inertia tender in Great Britain and macroeconomic aspects. Discussions will pick up on referenced literature from Sections 1.1 and 2.4.

In general, energy system modelling is a method already applied to assess power system inertia in future power systems. The ENTSO-E assessed power system inertia for Continental Europe by applying a post-process approach [38]. The methods applied in this dissertation project, especially the developed modelling tool OpInMod, mark a significant benefit to this research field. System inertia is variable over time and the actual level of power system inertia influences the power generation dispatch and vice versa with regard to the systems-defined critical inertia level and the necessity to balance power generation and demand. This is not reflected in the model output of the ENTSO-E [38]. Since OpInMod is an open-source modelling tool, it is simple to access and can be used in further research projects.

If considered at all in energy system modelling, only synchronous inertia has been depicted. OpInMod is the first unit commitment and economic inertia dispatch modelling tool able to depict SI provided by wind turbines and battery storage units. Different control logics to provide SI exist. The continuous inertia control approach developed by Gloe et al. is applied in this work due to its beneficial influence on the power system. The control approach avoids the disconnection of wind turbines for safety reasons in case of over- or underspeed occurrence [30, 31]. The control approach for SI by battery storage units is not further defined. With regard to the incremental time scale needed in this work, usually 1-hour time steps, the precise battery SI control approach is neglectable, since all control methods react within a few seconds and the adapt power output. Furthermore, the main costs occur not with regard to the applied control approach, but with regard to the energy storage system used to either absorb or provide energy [33]. A promising control approach are by grid-forming converters [39]. However, further research is needed to assess the approach on a full system scale and further, energy storage systems are still necessary [21, 33, 35].

A design assumption proposed in Publication I and applied in Publication V is the principle of joint action, a minimum inertia constraint on a national level, although the researched system is part of a larger synchronous area. The research at hand has not considered and thus modelled the possibility to share inertia transnationally. Inertia-related costs could also be researched and determined by transmission capacities needed to provide necessary power via an inertia response from spatially distant locations. For instance, an analysis of transfer capacities between France and Germany, where France provides large shares of inertia via its nuclear power plant fleet.

The research performed assesses inertia provision in different regions, namely Continental Europe, Ireland and Germany. Due to computational limitations, the work carried out in Publications III to V could not be performed for Continental Europe. However, although inconsistent with regard to the regions assessed, the results are representative and, at least in Continental Europe, are transferable between countries. Costs presented in Publication I occur independently from the researched region. Inertia-related system costs as analysed in Publications III to IV are, of course, a representation of the respective energy mix. Hence, a system with high marginal cost power generation units like natural gas-fired plants would have higher costs associated with inertia provision compared to a system consisting of low marginal cost generation units like lignite-fired power plants. However, since power systems are decarbonised and carbon dioxide-emitting power plants are replaced with wind turbines and photovoltaic systems, inertia-related system costs will be less dominated by fossil fuel-related costs and much more by storage systems providing inertia. These costs occur independently of the unit's geographical location. However, comparing e.g., the Continental European power system with the Nordic power system is more difficult. This is due to the fact that the Nordic system consists of a high share of hydropower plants and thus a higher share of renewable synchronously connected generation units. Thus, inertia-related system costs in the Nordic power system are likely lower and influenced by the opportunity costs of hydropower plants.

The results of Publications III to V represent only system costs related to the operation of units providing an inertia response. Hence, they cannot directly be compared with overall costs indicated in Publication I, since they include financing costs as well. However, when capital expenditures are excluded from the analysis of Publication I, operating-related costs result in $15.64\,€/(\mathrm{kg{\cdot}m^2})$. Comparing this value of $15.64\,€/(\mathrm{kg{\cdot}m^2})$ to results of Publication III with inertia relating costs ranging from $1.02\,€/(\mathrm{kg{\cdot}m^2})$ up to $4.49\,€/(\mathrm{kg{\cdot}m^2})$ and with costs concluded in Publication V ranging from $0.002\,€/(\mathrm{kg{\cdot}m^2})$ to $0.61\,€/(\mathrm{kg{\cdot}m^2})$, results are comparable. It has to be noted, that inertia-related costs in Publications III, IV and V represent overall mixed system costs. Hence, the results are lower due to the high share of inertia which is provided by low marginal cost driven wind turbines. Thus, SI provided by wind turbines reduces the system costs for inertia significantly.

The first publication determines the trading unit for the commodity inertia. It concludes with the appropriate unit for inertia being €/(kg·m^2). Related research also concluded that the moment of inertia is the appropriate trading unit [12]. Through the example of synchronous condensers and other non-energy related sources, it is stated that providers of inertia need an altogether different valuation and thus a price per power or a price per energy to trade inertia are excluded [12].

The Stability Pathfinder program by the TSO of Great Britain led to the purchase of synchronous inertia with a stored kinetic energy of 16.8 GWs for £ 574.6 million for a six-year period [19]. The inertia constant for each unit applied in the tender is known [19]. Rearranging Equation (2.2) for J_i results in an overall purchased moment of inertia of 1,070,913 kg·m^2. Hence, on average, the costs for inertia result in 125.93 €/(kg·m^2) per year[1]. This indicates that the results of the work at hand are reasonable. Both values include all costs of realising and operating such a system. Hence, all capital and operating expenditures. Especially the annual costs of the flywheel system in the first publication with 167.64 €/(kg·m^2) show a good fit, since the purchased inertia in the Great Britain system is provided via synchronous condensers equipped with flywheels.

A full analysis of power system inertia-related system costs would also include an assessment of macroeconomic impacts. For example, energy-intensive and thus system inertia-dependent national economies will be more affected by higher inertia-related costs. Thus, national economies in smaller isolated power systems likely have a locational disadvantage compared to national economies in larger synchronous areas.

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[1] An exchange rate of 1.17 €/£ is assumed.

5 Conclusion

The necessity to decarbonise energy systems is indisputable. Therefore, fossil fuel-fired power plants are being replaced with RES, to a large extent with frequency converter connected wind turbines and photovoltaic systems. As a consequence, power system inertia decreases due to the displacement of synchronously connected generators. Power system inertia is essential for grid frequency stability as it limits the ROCOF and the grid frequency peak or nadir. Some grid operators of low inertia power systems already have to take countermeasures in order to sustain the controllability of the grid frequency. Measures, for instance, are the introduction of critical system inertia levels, the installation of units providing an inherent inertia response or the requirement of a SI response from wind turbines.

So far, inertia provision is a by-product of power generation and is free-of-charge. If inertia provision is required from power generation or energy storage units in future power systems and is associated with additional expenditures, compensation is demanded for this service. Although many technical solutions exist to provide either synchronous inertia or SI, an economic assessment of costs for inertia is an open research area.

The findings of this dissertation project show that the provision of the currently free-of-charge grid service inertia is associated with costs in future energy systems and already has value. The costs for system inertia depend on the supply side on the inertia-providing sources and on the demand side on the required system inertia, hence the by the grid operator defined critical inertia level. Inertia provided by power consumers varies between different groups of power consumers and its provision reduces the demand for additional inertia. SI provided by wind turbines can significantly reduce system costs for inertia. The integration of synchronous condensers equipped with flywheels in combination with SI provision by wind turbines is the most cost-beneficial solution to provide total system inertia. Higher CO_2 emission prices need to be taken into account to achieve overall system decarbonisation. Overall, future research has to determine the most cost-efficient solution between dispatching additional units providing inertia, additional transmission capacities to transfer required power and the reduction of activation time of power reserve unit's associated costs.

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