1862

RIGA TECHNICAL
UNIVERSITY

Romāns Oļekšijs

MODERNISATION OF ELECTRIC EQUIPMENT OF COMBINED CYCLE UNITS FOR ADAPTION TO NEW ELECTRICITY MARKET REQUIREMENTS

Summary of the Doctoral Thesis

RTU Press
Riga 2020

RIGA TECHNICAL UNIVERSITY
Faculty of Electrical and Environmental Engineering
Institute of Power Engineering

Romāns Oļekšijs
Doctoral Student of the Study Programme "Power Engineering"

MODERNISATION OF ELECTRIC EQUIPMENT OF COMBINED CYCLE UNITS FOR ADAPTION TO NEW ELECTRICITY MARKET REQUIREMENTS

Summary of the Doctoral Thesis

Scientific supervisor
Assoc. Professor Dr. sc. ing.
OĻEGS LINKEVIČS

RTU Press
Riga 2020

Oļekšijs, R. Modernisation of Electric Equipment of Combined Cycle Units for Adaption to New Electricity Market Requirements. Summary of the Doctoral Thesis. Riga: RTU Press, 2020. 48 p.

Published in accordance with the decision of Promotion Council “RTU P-05” of 5 May 2020, Minutes No. 69/20.

The research has been conducted with the support of Latvian Council of Science project “Management and Operation of an Intelligent Power System” (I-POWER) (No. lzp-2018/1-0066) and the Ministry of Economics of the Republic of Latvia project “Future-proof development of the Latvian power system in an integrated Europe (FutureProof)”, Project No. VPP-EM-INFRA-2018/1-0005.

ISBN 978-9934-22-453-9 (print)
ISBN 978-9934-22-454-6 (pdf)

DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (Ph. D.), the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council on 29 June 2020 at 11.30 at the Faculty of Electrical and Environmental Engineering of Riga Technical University, 12 k-1 Azenes Street, Room 306.

OFFICIAL REVIEWERS

Senior Researcher Dr. sc. ing. Lubov Petrichenko
Riga Technical University, Latvia

Professor Dr. sc. ing. Saulius Gudzius
Kaunas University of Technology, Lithuania

Senior Researcher Dr. sc. ing. Arturas Klementavicius
Lithuanian Energy Institute, Lithuania

DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Science (Ph. D.) is my own. I confirm that this Doctoral Thesis had not been submitted to any other university for the promotion to a scientific degree.

Romāns Oļekšijs ……………………………. (signature)

Date: ………………………

The Doctoral Thesis has been written in English. It consists of 7 Chapters; Conclusion; 59 figures; 33 tables; the total number of pages is 135. The Bibliography contains 139 titles.

CONTENT

1. INTRODUCTION

1.1. Topicality of the Research

Combined cycle power plants (CCGT) in Latvia used to operate in the baseload regime until 2014 when Latvia joined the Nord Pool power exchange market. Change of market principles led to more cycling operations of power plants, which is typical to all open electricity markets. The European Union is in the pursuit of great improvements in energy efficiency and renewable energy use, which even more increases the number of CCGT operation cycles, due to intermitting solar and wind generation [1], [2], [45].

Cycling operation is more damaging for power plant equipment despite many improvements that have been made to make CCGTs adopt such operation mode. Problems with the thermal fatigue of heat recovery steam generators (HRSG) and steam turbines are well known and have been studied for decades [5]–[7]. Less attention is paid to the main electrical equipment of power plants, which may suffer from cycling operation as well [8], [9].

The European Commission implemented the Regulation (EU) 2016/631 of 14 April 2016, establishing a network code on requirements for grid connection of generators (RfG), which is a good example of understanding further challenges in the electrical power grid. RfG sets high requirements for all conventional and renewable generators because the power grid becomes weaker due to the market relationships, increased share of intermitting generation, high voltage direct current interconnections and disbalance of generation in regions [4], [23], [67].

The Baltic states are going to interconnect with the Continental Europe network (CEN), which with the most probability will result in application of RfG for existing generators. In some cases additional modernization must be made demanding additional investments from generators. Synchronization with CEN, however, will lead to changes in the ancillary service provision system. Provision of frequency primary and secondary control service, voltage control service, and inertia contribution service might become market based and lead to changes in power plant operating mode [22], [54].

Renewable energy may help to optimize power plant self-consumption reducing the costs of power plant operation. Even more possibilities are brought by using battery storage systems (BESS), which could allow reducing the costs for self-consumption as well as provide ancillary services [28], [30], [43], [74].

Use of additional gains from ancillary service provision and reduction of self-consumption electricity costs can allow CCGTs to move towards more stable operating modes, which could result in lower overall costs of operation or greater income.

In this Doctoral Thesis, the following questions and challenges were studied.

- Cycling operation impact on main electrical equipment of a power plant was analyzed. Based on available main electrical system reliability statistics of combined heat and power plants (CHP) empirical formulas were obtained to evaluate the impact of different operating regimes of CCGT, also outage and unplanned unavailability caused costs were evaluated. All this can be used for risk assessment.

- Possible ways of modernization of existing power plants to fulfill RfG and provide additional ancillary services were described. Analysis of possible service provision costs from CCGT and installations connected to the transmission system operator (TSO) were made.
- Solar generation data collection from the experimental installation was made and the methodology of detailed analysis of photovoltaic (PV) system profitability in CCGT self-consumption system was developed and tested on historical data providing essential information for economic calculations.
- PV system profitability methodology was enhanced by adding BESS operation evaluation module, which optimizes BESS operation to reduce self-consumption costs and maximize use of solar energy. This module operates as a separate program and optimizes BESS operation even during the hours when PV output is neglectable or zero. The enhanced methodology was tested on historical data and could be easily used with forecast data.
- Methodology for CCGT operation planning enhancement, which considers additional income from ancillary service provision, was developed and tested using historical data. Combining results of operation planning enhancement algorithms with empirical formulas for outage rate and caused costs calculation allow choosing the best operation strategy for CCGTs – move towards income maximization or to a reduction of startup number.

Provided analysis, calculations and developed solutions allow to improve the planning of CCGT operation and make decisions about future investments in power plant upgrades. The remuneration of ancillary services might have a huge impact on the future operation of CCGT.

1.2. Hypothesis of the Doctoral Thesis

Provision of ancillary service and reduction of electricity self-consumption costs allows more optimal CCGT operation, reduction of outage rate and extra costs, as well as provide additional profits. To ensure provision of ancillary services, modernization of existing CCGT electrical equipment is required.

1.3. The Aim of the Doctoral Thesis

This Doctoral Thesis aims to analyze the cycling operation impact on CCGT's main electrical equipment and develop tools to evaluate this impact, as well as consider upcoming challenges and changes in legislation and in grid interconnection. It requires development of a new methodology for economic calculations of ancillary service provision for evaluation of the feasibility of proposed modernizations options. Another important target of this Thesis is the development and validation of the methodology for detailed profitability calculations of

PV generation and BESS for power plant self-consumption. The main target is the use of developed methodologies in the methodology for CCGT operation planning enhancement, which allows choosing an operation strategy.

1.4. The Task of the Doctoral Thesis

To achieve the aims of the Doctoral Thesis, the following tasks were set:

- to study the degradation process in electrical equipment and reliability statistics of combined heat and power plant main electrical equipment;
- to evaluate the outage rate of main electrical equipment and caused costs;
- to overview the new requirements set up by RfG and possible technical constraints for existing power plants as well as the measures to overcome them;
- to analyze the possibilities and costs of ancillary service provision from existing CCGT;
- to develop and verify the methodology for evaluation of the feasibility of solar generation use in thermal power plant for provision of self-consumption, based on the collected data from the PV system deployed for an experiment;
- to develop and verify the methodology for evaluation of feasibility of BESS use for power plant self-consumption;
- to develop a methodology for maximization of income from provision of ancillary services and minimize CCGT number of startups/shutdowns.

1.5. Scientific Novelty

The study on incident and failure causers as well as statistics of main electrical equipment of combined heat and power plant was conducted. Within the study, new calculation methodology, which uses empirical formulas to evaluate the influence of power plant operating modes on outage rate, as well as evaluation of associated outage costs, were developed.

Methodology for technical and economic evaluation of the proposed solutions for modernization, which allow to fulfil RfG requirements of existing power plants, have been developed.

Various solutions of ancillary service provision from CCGT were analyzed and possible costs of voltage control, primary frequency control, and inertia services provision were calculated.

Methodology for evaluation of PV generation and its possible contribution to self-consumption of the thermal power plant has been developed and verified using the data from the PV system installed in Riga TEC-2 as an experiment. The methodology uses PV hourly generation and electricity self-consumption volumes for feasibility evaluation of PV system in a thermal power plant.

The developed methodology was extended to optimize the BESS operation in combination with PV generation as well as in standalone operation mode to ensure lower costs for thermal power plant electricity self-consumption. The methodology was verified using historical hourly data.

Methodology for CCGT operation planning enhancement, based on additional income from ancillary service provision, has been developed and verified on hourly historical data. Previously developed empirical expressions were applied to calculation results to evaluate the outage rate of CCGT main electrical equipment and associated unavailability costs due to shifting in operation.

1.6. Practical Significance of the Research

The obtained empirical formulas for evaluation of outage rate of CHP main electrical equipment as well as the evaluated costs of caused unavailability can be used in risk assessment management, giving a better understanding of cyclic operation consequences for combined cycle power plants.

Solutions were proposed for modernization of existing combined cycle power plants in order to fulfill new grid connection requirements and possible changes in power plant operation due to synchronization of the Baltic power system with CEN that could be implemented in 2025. The developed methodology was used to evaluate possibilities and costs of ancillary service provision from existing CCGTs after modernization and from sites connected to TSO. Costs of service provision were used to evaluate possible income for CCGT in case the ancillary services become remunerated in the future.

The developed methodology for evaluation of electricity supply from PV system to ensure self-consumption of thermal power plant could be used for different applications to estimate in detail the feasibility of such solution, as well as to allow selection of optimal power of photovoltaic system. The proposed methodology was used for evaluation of feasibility of photovoltaic systems in Riga TEC-2, which were installed during 2017−2019. The methodology for BESS operation optimization to reduce self-consumption electricity cost was developed. The interaction of both methodologies gives even more possibilities to reach ecological targets.

The methodology for CCGT operation planning enhancement based on the income from ancillary service provision was developed. It allows moving towards maximal profit from service provision or the lowest number of start-up/shut down operations. The developed empirical equation should be used to evaluate the impact of the results of both solutions on the main electrical equipment outage rate and caused costs, which will give an understanding of possible CCGT operation strategy for the planning period.

The methodologies developed in this Doctoral Thesis were mainly applied to JSC “Latvenergo” power plants, but they can be used for any other similar generation facilities. Realization and verification of the developed methodologies were made by developed C# programs, which as data source use MS Excel databases, the results are extracted as MS Excel worksheets, which makes the developed programs easy applicable for any new object of research.

1.7. Volume and Structure of the Doctoral Thesis

The Doctoral Thesis is written in English. It comprises seven chapters, thirty three sections, conclusions and bibliography with 139 reference sources. It has been illustrated by 59 figures and 33 tables. The volume of the Thesis is 135 pages.

Chapter 1 provides information about topicality and hypothesis of the Thesis, formulates the aim of the research and tasks to be fulfilled. Also, scientific novelty and practical significance of the Thesis are presented. Author's scientific works are listed.

Chapter 2 provides an overview about the challenges arising from the cycling operation mode to CCGT main electrical equipment. Also new requirements for generators are briefly overviewed. Information about possible solutions for ancillary service provision and CCGT self-consumption electricity costs reduction is provided.

Chapter 3 presents a detailed overview of different stress impact on main electrical equipment of CHP. Based on statistics, empirical formulas for outage rate approximation were obtained. The costs of outage caused unavailability are estimated as well.

Chapter 4 describes the problems that arise for existing generators from new requirements, as well as calculations for possible solutions. Economic impact of power plant modernization is considered.

Chapter 5 provides a description of possible ancillary service provision from CCGT to the grid. Ancillary service provision alternatives are analyzed and service costs for Latvia are evaluated.

Chapter 6 focuses on reducing CCGT self-consumption costs as well as greenhouse gas emission footprint. A methodology developed for detailed feasibility evaluation of photovoltaic system is presented. This methodology is also enhanced by the algorithm for joint optimization of battery storage and photovoltaic system. An example of calculations using the developed methodology is provided.

Chapter 7 summarizes the results of the Doctoral Thesis and provides a methodology for CCGT operation planning enhancement based on possible income from ancillary service provision, combining the results with outage rate evaluation and possible unavailability costs.

1.8. Scientific Work

The results of the research have been presented at international scientific conferences in Latvia and abroad:

1. 2019 IEEE 7th IEEE Workshop on Advances in Information, Electronic and Electrical Engineering (AIEEE), 15−16 November 2019, Liepaja, Latvia
2. 2019 IEEE 60th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), 7−9 October 2019, Riga, Latvia
3. 2018 IEEE 59th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), 12−13 November 2018, Riga, Latvia.

4. 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), 12−15 June 2018, Palermo, Italy.
5. 2016 57th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), 13−14 October 2016, Riga, Latvia.

During the doctoral studies, the author has participated in other international conferences, where the topical energy sector problems have been discussed:

1. 2017 IEEE 58th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), 12−13 October 2017, Riga, Latvia.
2. 2015 IEEE 5th International Conference on Power Engineering, Energy and Electrical Drives (POWERENG), 11−13 May 2015, Riga, Latvia.
3. 2014 55th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), 14 October 2014, Riga, Latvia.

The results of the research have been published in conference proceedings:

1. R. Oļekšijs and B. Olekshii, “Combined heat and power plant electrical equipment incident rate and unavailability empirical expression,” 2019 IEEE 7th IEEE Workshop on Advances in Information, Electronic and Electrical Engineering (AIEEE), 15−16 November 2018, Liepaja, Latvia, Electronic ISBN: 978-1-7281-6730-5, doi: 10.1109/AIEEE48629.2019.8976989.
2. R. Oļekšijs and O. Linkevičs, “Possible solutions for ancillary service provision from combined heat and power plants in Latvia,” 2019 IEEE 60th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), 7-9 October 2019, Riga, Latvia, Electronic ISBN: 978-1-7281-3942-5, doi: 10.1109/RTUCON48111.2019.8982358.
3. R. Oļekšijs and O. Linkevičs, “Photovoltaic system application for combined heat and power plant self-consumption needs,” 2019 IEEE 60th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), 7−9 October 2019, Riga, Latvia. Electronic ISBN: 978-1-7281-3942-5, doi: 10.1109/RTUCON48111.2019.8982371.
4. Oļekšijs, R., Linkevičs, O. Photovoltaic system application for industry self consumption needs. In: 2018 IEEE 59th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), 12−13 November 2018, Riga, Latvia. Piscataway: IEEE, 2018, Electronic ISBN: 978-1-5386-6903-7, doi: 10.1109/RTUCON.2018.8659909.
5. Makalska, T., Varfolomejeva, R., Oļekšijs, R. The Impact of Wind Generation on the Spot Market Electricity Pricing. In: 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), 12−15 June 2018, Palermo, Italy.

Piscataway: IEEE, 2018, Electronic ISBN: 978-1-5386-5186-5, doi: 10.1109/EEEIC.2018.8494539.

6. Oļekšijs, R., Linkevičs, O. Failure simulation model for evaluation of CHP electrical equipment reliability. In: 57th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), 13−14 October 2016, Riga, Latvia. Piscataway: IEEE, 2016, Electronic ISBN: 978-1-5090-3731-5, doi: 10.1109/RTUCON.2016.7763139.

The author's articles have also been published in conference proceedings, where different problems concerning the energy sector have been considered:

1. Krickis, O., Oļekšijs, R. Safe operation of the industrial centrifugal pump sets in parallel connection. In: 2017 IEEE 58th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), 12−13 October 2017, Riga, Latvia. Piscataway: IEEE, 2017, Electronic ISBN: 978-1-5386-3846-0, doi: 10.1109/RTUCON.2017.8124774.
2. Sauhatas, A., Oļekšijs, R. Hallways and stairways lighting system cost reduction. In: 2016 57th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), 13−14 October 2016, Riga, Latvia. Piscataway: IEEE, 2016, Electronic ISBN: 978-1-5090-3731-5, doi: 10.1109/RTUCON.2016.7763150.
3. Olekshii, R., Linkevičs, O., Kukļa, N. Utilization of latent heat of 330 kV autotransformer for space and water heating in substation Imanta. In: 2015 IEEE 5th International Conference on Power Engineering, Energy and Electrical Drives (POWERENG), 11−13 May 2015, Riga, Latvia. Piscataway: IEEE, 2015, Electronic ISBN: 978-1-4799-9978-1, doi: 10.1109/PowerEng.2015.7266295.
4. Olekshii, R., Linkevičs, O., Kukļa, N. Feasibility of usage of thermoelectric modules for recovering of low-potential heat from a surface of power transformers. In: 2014 55th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), 14 October 2014, Riga, Latvia. Piscataway: IEEE, 2014, Electronic ISBN: 978-1-4799-7462-7, doi: 10.1109/RTUCON.2014.6998217.

2. CHALLENGES FOR CCGT ELECTRICAL EQUIPMENT

2.1. Cycling Operation Impact on Electrical Equipment

Modern CCGTs are designed for a two-shift operation mode, this type of operating is more damaging for power plant equipment. It is well known that thermal fatigue is at its most damaging when a component is operating in the creep range and is subject to a constant tensile load. This mostly affects gas and steam turbines as well as HRSG [5]–[7]. Impact on power plant electrical equipment is not studied as much. Generator and switchgear can be susceptible to increased fatigue, wear, and other forms of degradation due to repeated stop-start operation [8], [9].

VGB presented its technical-scientific report “Analysis of Unavailability of Power Plants 2008−2017”. Table 2.1 presents data for 53 CCGTs in Europe [11]. Despite that, total incident count for main electrical equipment is only 1.22 incidents per unit (according to VGB one unit is power plant unit, not equipment) per year, which is 3.15 % of all incidents, it causes 0,97 % of unavailability, which is 12.6 % of total power plant unavailability.

Table 2.1

Unavailability Report for CCGT for 2008−2017

	Unavailability incidents			**Energy unavailability, %**		
	not postponable	**postponable**	**total**	**not postponable**	**postponable**	**total**
Generator system	0.53	0.09	**0.62**	0.5	0.21	**0.71**
of them generator				*0.28*	*0.13*	***0.41***
Main supply system	0.42	0.18	**0.60**	0.26		**0.26**
of them main transformer				*0.12*		***0.12***
Main electrical system, total	**0.95**	**0.27**	**1.22**	**0.76**	**0.21**	**0.97**
Power plant, total	33.3	5.4	38.70	6	1.7	7.7

Generator must operate under electrical, mechanical and thermal stress all the time. The majority of problems occur with generator insulation. Usual stator defect is improper impregnation of insulation, which is a manufacturing defect; thermal deterioration (Fig. 2.1 a), which usually is the result of winding short circuits and sometimes is the result of bad cooling; delamination of insulation from copper (Fig. 2.1 b), which usually is forced by cycling loading and unloading of generator, different thermal expansion coefficients of copper and mica lead to additional mechanical stress of insulation and results in crack developing and delamination. Also, ground painting problems (Fig. 2.1 c), slot vibration (Fig. 2.1 d), end winding vibration (Fig. 2.1 e), problems with corona protection, contamination, and insufficient spacing lead to the development of defects [13]–[15].

Fig. 2.1. Common generator stator defects [13], [15].

According to [11] the main supply system causes 3.38 % of power plant unavailability time, power transformers represent 1.55 % of 3.38 %. The weakest spots or elements of power transformer are represented in Fig. 2.2 [16]–[18]. For CHPs [19] the reported failure rate is 0.094 per unit per year.

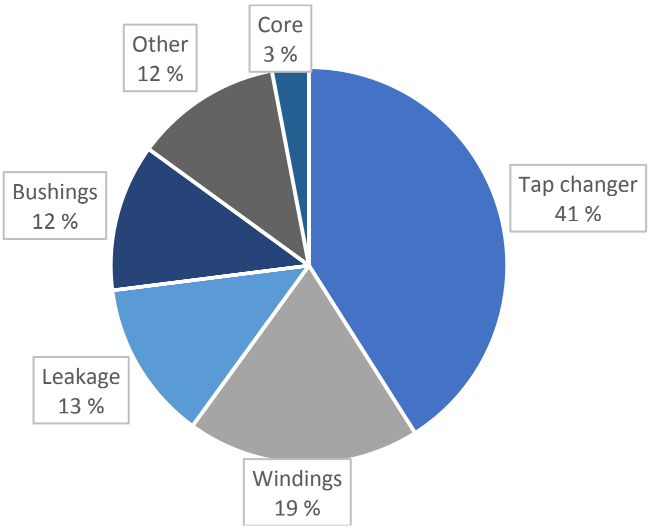

Fig. 2.2. Power transformer subcomponent failures [17].

Main circuit breakers cause very few problems for power plants [10], [11]. Usually the circuit breaker problem occurs when an operation command is performed. In some cases circuit breakers lock and do not perform task operation due to failure or blocking within the circuit breaker control system, such failure mode represents 25 % of CB failures.

2.2. Transmission Grid Development and Ancillary Services

The European Commission implemented the Regulation (EU) 2016/631 establishing a network code on requirements for grid connection of generators (RfG). RfG sets high requirements for all conventional and renewable generators [4]. RfG can be implemented to existing power plants in Latvia after synchronization with the CEN in 2025 due to significant changes in transmission system [22].

In [23] it is stated, that in the case of the successful development of the scenario of 2025 for the Latvian energy system, taking into account additional interconnection lines and increasing the share of renewable energy sources, weak nodes and lines will appear. It will lead to problems with system static stability and balance of the system.

Also, synchronization with CEN will open new ancillary service markets. The Baltic balancing energy market, so called CoBA has already been launched providing frequency restoration reserves with manual activation (mFRR), the results show positive impact [25]. According to [24] frequency restoration reserves with automatic activation (aFFR) and frequency containment reserve (FCR) markets should be launched next. In future TSO might demand more reactive power compensation from generators and buy it as ancillary service [22], [24].

2.3. Optimization of Self-Consumption

Optimization of self-consumption allows reducing short term costs for power plants. It could be done in several ways. But most solutions depend on specific situations, especially when used for modernization or retrofitting in existing facilities [27].

European policies, photovoltaic global price reduction, and CO_2 market raise the interest to use solar power for self-consumption. Such solution is applicable to any facility with unused area. PV systems are widely used for business centers and industrial facilities to reduce electricity costs [28], [29]. Battery storage systems give even more possibilities to optimize electricity consumption [30].

BESS is well known for usage in combination with an intermitting source of energy. Such combination allows shaving peaks [43]. Also, BESS is used for off-grid solutions to provide as much energy as possible from renewable energy sources [44].

3. CHP ELECTRICAL EQUIPMENT RELIABILITY

CHP equipment degradation is studied by numerous works, e.g. [31]−[34], but mostly concerns gas turbine, heat regeneration steam generators, steam turbines outages and caused costs. [33] provides information about generator failure probability distribution and caused outage, thus no dependency on cyclic operation is presented. Some CHP outage analysis works takes into account generator failures, like [35] and [36], which also considered power transformer failures, thus, in both works electrical equipment failure rates are estimated just to approve the proposed methodology. [38] focuses on the development of generator outage model for risk-based maintenance, but generator failure rate also is estimated and has no relation to power plant operating modes. Therefore, [9], [13] and [14] discuss turbo-generator failures as a result of manufacturing, maintenance, installation or operating regimes; thus, lack of statistics does not allow to use these data for generator failure rate estimation.

For power transformers great failure rate statistics are collected in [18] and statistics for circuit breakers and analysis is available in [16] and [20]. That is why in this Doctoral Thesis focuses on generator incident rate analysis. Also, economic impact of CHP's main electrical equipment incident rate is analyzed [21].

3.1. Approach of Incident Rate and Unavailability Evaluation

Fig. 3.1 shows that the generator incident rate is not a regular function of operating hours. It is the same if the generator incident rate is presented as a function of start-up number. It is because of the difference of generator constructions, age and operating regimes represented in statistics; incident rate of generators, in general, can be expressed as follows:

$$\lambda_{\mathrm{gen}} = f\left(t_{\mathrm{op}}; n_{\mathrm{s}}; c; y; t_{\mathrm{t}}; \ldots\right), \tag{3.1}$$

where

λ_{gen} – generator incident rate;

t_{op} – operation time per year, h per year;

n_{s} – number of starts per year;

c – cooling method (direct or indirect);

y – insulation technology;

t_{t} – total number of hours in operation, h.

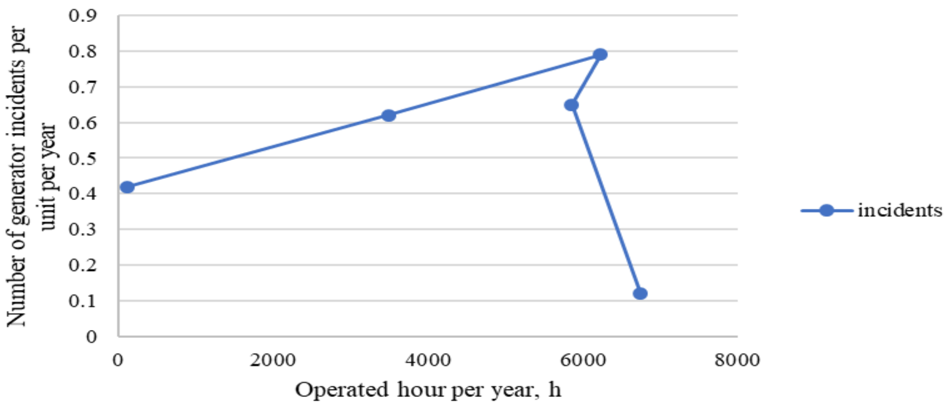

Fig. 3.1. Number of generator system incidents per year per unit relation to operating hours per year.

As it is not possible to describe the generator incident rate from a physical model or it is too complicated to be applied in practice, the empirical model can be used to evaluate the relations between different variables (start-up number and operating hours) to describe the incident rate. In this Doctoral Thesis, least square method and proposed approach are used to find out the empirical formula for turbogenerator incident rate and unplanned unavailability time [37]. Using the least square method incident rate would be expressed as

$$\lambda_{\mathrm{gen.l}} = \beta_0 + \beta_1 t_{\mathrm{op}} + \beta_2 n_{\mathrm{s}}, \tag{3.2}$$

where

$\lambda_{\mathrm{gen.l}}$ – incident rate calculated by least square method;

β – unknown parameters of empirical model.

In the proposed approach it is suggested to get rid of the number of operating hours or the number of starts, to get more clear dependency of incident rate on one of the two proposed variables. The used statistics clearly defines average operated hours per year, but the number of startups was evaluated from several sources, so operating hours were used as a base for further calculation. A graph as in Fig. 3.2 was obtained.

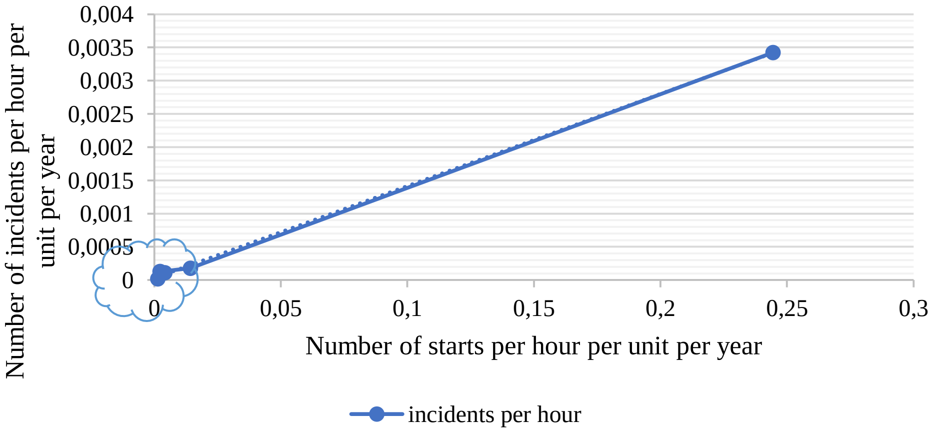

Fig. 3.2. Number of generator system incidents per hour per year per unit relation to the number of starts per hour per unit per year.

The hourly incident rate is

$$\lambda_{\text{gen.h}} = \frac{\lambda_{\text{gen}}}{t_{\text{op}}} = f\left(\frac{n_{\text{s}}}{t_{\text{op}}}\right). \tag{3.3}$$

The results obtained from available statistics data were divided in linear segments and an expression for each were calculated. For incident estimation per hour per unit per year Table 3.1 must be used.

Table 3.1

Equations for Incident Rate Estimation for Generators

Number of starts per hour per unit per year	**$\lambda_{\text{gen.h}}$ estimation equation**	**Equation number**
0.000 741 to 0.004 272	$0.0264n_{\text{s.h}} - 0.000\,002$	1
0.004 272 to 0.014 341	$0.0066n_{\text{s.h}} + 0.000\,08$	2
0.014 341 to 0.570 776	$0.0058n_{\text{s.h}} + 0.000\,09$	3

In case the least square method is used, the following expression will be obtained:

$$\lambda_{\text{gen.l}} = -1.92807 + 0.00029t_{\text{op}} + 0.03266n_{\text{s}} \tag{3.4}$$

The least square method allows to get empirical relation in a shorter time and allows to use one common expression instead of three different formulas for different occasions as it should be done for the proposed approach. Simulation of different operating regimes and using the proposed approach formulas from Table 3.1 and least square method (3.4) show that the obtained incident rate for different operating regimes than the one used for empirical formula estimation differs a lot. Fig. 3.3 presents the calculated generator incident rate dependence on operating hours.

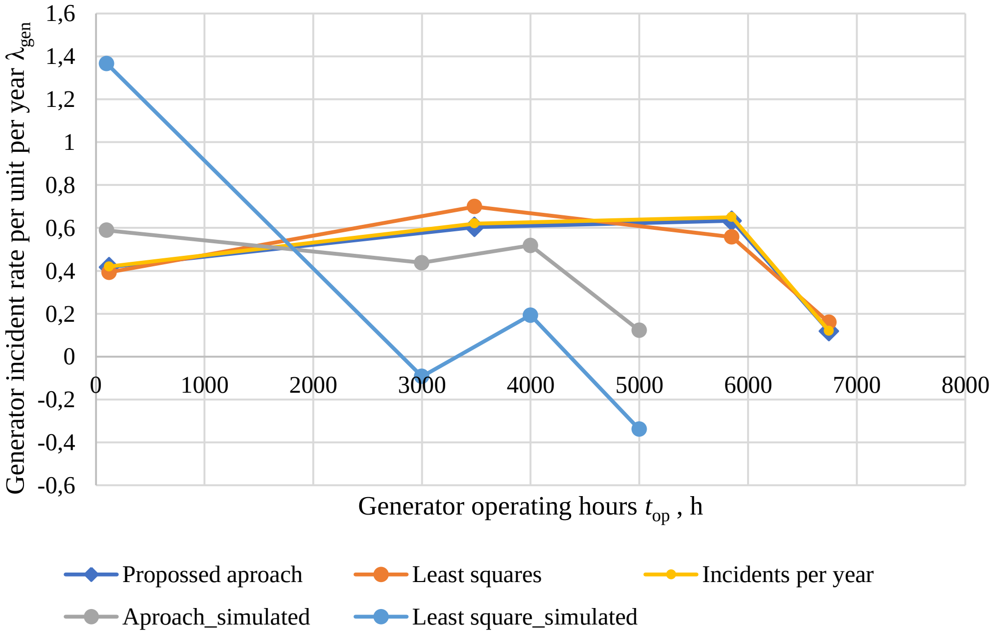

Fig. 3.3. Comparison of results of the proposed approach and least square results for generator incident rate estimation.

Total incident rate of power plant unit main electrical equipment is calculated as follows:

$$\lambda_{\mathrm{el.t}} = \lambda_{\mathrm{gen}} + \lambda_{\mathrm{t}} + \lambda_{\mathrm{cb}} = \lambda_{\mathrm{gen.h}} t_{\mathrm{op}} + \sum_{i=1}^{n} \lambda_{\mathrm{t.v}} + n_{\mathrm{s}} \sum_{i=1}^{n} \lambda_{\mathrm{cb.o}}, \quad (3.5)$$

where

$\lambda_{\mathrm{el.t}}$ – main electrical equipment total incident rate per unit (block) per year;

λ_{gen} – generator incident rate per unit (block) per year calculated by Table 3.1;

λ_{t} – step-up power transformer failure rate per unit (equipment) per year;

λ_{cb} – generator circuit breaker failure rate per unit (equipment) per year;

n – total amount per power plant unit (block);

$\lambda_{\mathrm{t.v}}$ – step-up transformers failure rate according to the voltage level of step-up transformer;

$\lambda_{\mathrm{cb.o}}$ – generator circuit breaker failure rate according to circuit breaker technology.

The circuit breaker failure rate is very low, so this part could be ignored in risk assessment.

For generator outage caused unavailability percentage estimation, the same approach is used that was used for generator incident rate estimation.

$$k_{\mathrm{un.h}} = \frac{k_{\mathrm{un}}}{t_{\mathrm{op}}} = f\left(\frac{n_{\mathrm{s}}}{t_{\mathrm{op}}}\right), \quad (3.6)$$

where $k_{\mathrm{un.h}}$ is hourly energy unavailability percent per unit (block) per year caused by generator, %.

The obtained equations are presented in Table 3.2. The next step is calculation of unavailable or unproduced energy due to estimated failure rate, which is done using (3.8).

Table 3.2

Equations for Unavailability Estimation for Generators

Number of starts per hour per unit per year	**Unavailability % estimation equation**	**Equation number**
0.000 741 to 0.004 272	$0.0148 n_{\mathrm{s.h}} + 0.000\,007$	1
0.004 272 to 0.014 341	$0.0133 n_{\mathrm{s.h}} + 0.000\,01$	2
0.014 341 to 0.570 776	$0.0204 n_{\mathrm{s.h}} – 0.000\,09$	3

Generator unavailability expressions obtained by least square method were calculated.

$$k_{\mathrm{un.l\_v2}} = -0.30140 + 0.00005 t_{\mathrm{op}} + 0.01674 n_{\mathrm{s}}, \quad (3.7)$$

where $k_{\mathrm{un.l}}$ is generator caused energy unavailability percent per unit per year calculated by least square method, %.

In case of caused unavailability calculation it is also proposed to use Table 3.2 expressions.

$$W_{\mathrm{un.e}} = k_{\mathrm{un.e}} P_{\mathrm{N}} t_{\mathrm{N}}, \quad (3.8)$$

where

$W_{\mathrm{un.e}}$ – estimated unavailable energy per unit per year due to generator incidents, MWh;

$k_{\mathrm{un.e}}$ – estimated incident caused energy unavailability percent, %;

P_{N} – power plant unit nominal power, MW;

t_{N} – calendar time, h [11].

As power transformer failure rate does not depend on cycling operation, average energy unavailability of main transformer was taken as constant 0.12 % according to [14]. Circuit breaker failure caused energy unavailability is not represented in statistics due to negligible failure rate [20].

3.2. Incident and Unavailability Caused Costs

Costs of unplanned unavailability could be divided into two groups: 1) additional maintenance and repair costs; 2) loss of income due to incident. Unavailability costs are expressed as follows:

$$C_{\mathrm{un}} = \lambda_{\mathrm{gen}} C_{\mathrm{mr.gen}} + \lambda_{\mathrm{t.110}} C_{\mathrm{mr.t110}} + \lambda_{\mathrm{t.330}} C_{\mathrm{mr.t330}} + t_{\mathrm{un}} P_{\mathrm{N}} C_{\mathrm{bal}} + \lambda_{\mathrm{el}} C_{\mathrm{s}} + t_{\mathrm{un}} C_{\mathrm{ser}}, \qquad (3.9)$$

where

C_{un} – unavailability costs, EUR;

$C_{\mathrm{mr.gen}}$ – maintenance and repair costs per one generator incident, EUR;

$C_{\mathrm{mr.t}}$ – maintenance and repair costs per power transformer failure, EUR;

t_{un} – unplanned unavailability hours per year, h;

C_{bal} – balancing costs, EUR/MWh;

C_{s} – power plant unit startup costs, EUR;

C_{ser} – costs of loss due to undelivered ancillary services, EUR/h.

In [39] generators incident costs were reported as 140 794 EUR per incident. As power transformer statistics were provided for significant failures, the costs of failure are assumed as replacement costs of power transformer, costs of step-up power transformers are 15 000 EUR/MVA [71].

According to [22] average balancing price for upwards activation in Latvia in 2018 was 59.27 EUR/MWh. According to data from [40] incidents can lead to warm start of CHP, for 400 MW CCGT it will result in startup costs of approximately 32 040 EUR. Using equations from Table 3.1 and Table 3.2 calculations of incident caused costs for 400 MW CCGT block with 180 MVA 110 kV power transformer and 330 MVA 330 kV power transformer were made and provided in Table 3.3. The costs of unplanned unavailability time takes most share of incident and total unavailability caused costs.

Table 3.3

Incident and Unavailability Total Costs

Predicted operating hours per year	**Predicted starts per year**	λ_{gen}	$\lambda_{t.110}$	$\lambda_{t.330}$	$\lambda_{el.t}$	t_{un}, **h**	C_{un}, **total costs per year, EUR**	C_{un}, **total costs per 10 years, EUR**
2000	10	0.226	0.0059	0.0132	0.2451	23.9148	762 240	7 622 408
2000	30	0.354	0.0059	0.0132	0.3731	48.3552	1 402 754	14 027 549
2000	100	0.760	0.0059	0.0132	0.7791	173.448	4 562 196	45 621 966
3000	10	0.258	0.0059	0.0132	0.2771	25.3164	810 740	8 107 402
3000	30	0.438	0.0059	0.0132	0.4571	48.0924	1 436 608	14 366 089
3000	100	0.850	0.0059	0.0132	0.8691	165.564	4 418 230	44 182 304
4000	10	0.256	0.0059	0.0132	0.2751	25.9296	824 323	8 243 236
4000	30	0.518	0.0059	0.0132	0.5371	48.9684	1 495 552	14 955 528
4000	100	0.940	0.0059	0.0132	0.9591	157.6800	4 274 264	42 742 641

To prevent or minimize the number of incidents in power plant generators and step-up transformers, as well as to predict and control the degradation of insulation and other elements, numerous methods are used. Generally, they can be divided into online and offline monitoring [18], [46], [47], [49]–[51].

4. NEW REQUIREMENTS FOR GENERATORS

Development of electric grid, wider usage of renewable energy source, as well as new interconnections lead to changes in existing electricity markets. Energy systems become more vulnerable and grid stability is challenged. In [3] reasons and consequences of changes in modern energetics are discussed, such studies were carried out also for Latvia and are presented in [23], [67], [68].

The European Commission supports ENTSO-E actions in development of technical requirements for grid connected users to ensure greater security of electrical systems [52]. For existing generators compliance to some of new requirements might be problematic. Basing on information provided in [76] it can be concluded that the Baltic states synchronization with CEN will lead to the necessity to ensure higher existing generator security level to provide grid stability.

4.1. Possible Solutions for Existing Equipment to Meet New Voltage Control and Reactive Power Demands

To fulfill RfG voltage and reactive power requirements, three main problems need to be solved for existing generators:

1) high overvoltage up to 17 %, such overvoltage can be a cause for protection operation and can lead to trip of power plant;
2) great overcurrent (5–14 %) at undervoltage mode;
3) generator inability to consume / generate enough reactive power to fulfill U-$Q/P_{\max}$ requirements.

The target is to maintain overvoltage within 10 %, which could be done by choosing the appropriate tap of step-up transformer. Overcurrent below 5 % in any operating mode could be maintained if reactive power is compensated from other source, the same will help to provide reactive power to fulfil U-$Q/P_{\max}$ diagram requirements.

Step-up transformer contribution in reactive power consumption is expressed as follows:

$$Q_{\text{grid}} = Q_{\text{mg}} - \frac{x_{\text{T}}\left(P_{\text{g}}^2 + Q_{\text{gm}}^2\right)U_{\text{g1}}^2}{U_{\text{g2}}^2 S_{\text{g}}}, \tag{4.1}$$

where

Q_{mg} – reactive power to fulfill operation mode (in the case of leading operating mode the sign before reactive power should be changed to opposite), MVAr;

P_{g} – generator rated active power, MW;

U_{g1} – generator rated voltage, kV;

U_2 – generator voltage to fulfill RfG requirements, kV;

Q_{grid} – reactive power at generator connection point to the grid, MVAr;

x_{T} – step-up transformer reactance, Ω.

Table 4.1

Necessary Reactive Power Compensation Amount and Investments for Different Solutions

	***Q* comp. leading, MVAr**	***Q* comp. lagging, MVAr**	**Investments, EUR**			
			Capacitor bank / reactor	**SVC**	**STATCOM**	**Synchronous compensator**
Industrial type turbine generator (lead cosφ = 0.93; lag cosφ = 0.80), 110 kV grid	0	12	198 000	858 000	1 122 000	462 000
Heavy duty turbine generator (lead cosφ = 0.97; lag cosφ = 0.78), 110 kV grid	–15	4	313 500	1 072 500	1 402 500	962 500
Heavy duty turbine generator (lead cosφ = 0.91; lag cosφ = 0.84), 330 kV grid	–80	50	2 145 000	7 150 000	9 350 000	5 390 000

The amount of compensated reactive power for different generators and possible investments for different technologies, which will help generators to fulfill RfG requirements, are presented in Table 4.1. Synchronous compensators could not provide full rated power in leading regime, so higher rated power is chosen to fulfill the requirements [55]–[57].

4.2. Frequency Ranges and Ramping Challenges for Existing Equipment and Possible Solutions

Industrial gas turbine ramp rate according to Siemens is 5 % of CCGT block rated active power per minute, which is lower than 8 % in 30 seconds demanded by Latvian TSO [61]. Battery energy storage systems (BESS) could provide significant improvement in ramping speed for industrial type gas turbines [53], [60], [61].

To choose the right BESS for ramping speed improvement, several calculations should be made to understand power and capacity of installations. BESS power for ensuring proper ramping rate can be calculated as follows:

$$P_{\mathrm{B.r}} = k_{\mathrm{p}}(P_{\mathrm{d.r}} - P_{\mathrm{GT.r}}), \tag{4.2}$$

where

$P_{\mathrm{B.r}}$ – power of BESS used for ramping rate improvement, MW;

k_{p} – coefficient to prevent lack of power, used 1.05;

$P_{\mathrm{d.r}}$ – demanded power gain per 1 minute, MW;

$P_{\mathrm{GT.r}}$ – GT power gain per 1 minute, MW;

BESS should have enough capacity to perform within the time span while gas turbine will reach the demanded power:

$$A_{\mathrm{B.r}} = k_{\mathrm{c}} \sum_{t=0.0083}^{T} (t_{\mathrm{a}} P_{\mathrm{d.r}} - t P_{\mathrm{GT.r}}), \tag{4.3}$$

where

$A_{\mathrm{B.r}}$ – BESS capacity for ramping rate provision, MWh;

t_{a} – time to activate frequency demanded active power, h.

k_{c} – coefficient to prevent overcharge and under discharge of BESS, used 1.3;

T – time to reach $P_{\mathrm{d.r}}$ using only gas turbine ramping speed $P_{\mathrm{GT.r}}$, h.

For example, for 150 MW CCGT with 5 % per minute ramping rate of gas turbine according to (4.2) and (4.3), BESS should be at least 11.81 MW and 0.243 MWh, rounding up the results in 12 MW and 0.25 MWh. According to [26] investments for such BESS will be around 3 480 000 EUR.

5. ANCILLARY SERVICE PROVISION

In [41], [62]–[64], the necessary ancillary services to provide greater power system stability are discussed. Ancillary services from power plants and other users, mainly energy storage systems, connected to TSO become more and more important.

A thorough study of ancillary service provision situation is provided in [63], voltage and frequency control are covered, but service prices are not mentioned. Therefore [62] concentrates more on choosing a proper ancillary service market model and the presented prices for balancing and spinning reserve are just assumed as possible prices from generators. In [64] it is stated that BESS also can contribute in different ancillary service provision, but no service costs are mentioned as well.

R. Petrichenko, K. Baltputnis, D. Sobolevsky and A. Sauhats in [65] present the studies on possible costs of spinning reserve provision (that could provide inertia, frequency restoration reserves (FRR), frequency containment reserves (FCR), and reactive power) from the biggest Latvian hydro power plant (HPP) cascade. However, only costs of HPP are considered, the costs of the same service provision from CCGT or TSO connected parties are not considered. Reactive power costs provided from synchronous generators are evaluated in [66]. The study presented in [59] makes a comparison with possible service provision from generators and capacitor banks.

5.1. Reactive Power Control

Calculations for existing CCGTs show that the change of power factor from 1 to the rated will lead to additional costs per MVArh. For generators connected to 110 kV grid additional costs would result in up to 0.39 EUR/MVArh in lagging mode at rated active power and power factor, in leading mode additional costs would vary in the range from 0.06 EUR/MVArh to 0.20 EUR/MVArh. For the generators connected to 330 kV grid reactive power the price in lagging mode is moving from power factor 1 to rated is 0.51 EUR/MVArh and 0.17 EUR/MVArh in the leading mode. The costs are given at the cost of 50 EUR/MWh for active power production.

Calculations show that it is more economically feasible to make an upgrade for system security at the site connected to TSO and do not remunerate generators for reactive power provision. Results are presented in Table 5.2. It is due to very high costs of existing generators in order to comply with RfG, discussed in Subsection 4.1.

Table 5.1

Comparison of Reactive Power Price at Site Connected TSO and Generators Site if Reactive Power Provision is not Market Based and TSO Should Ensure Grid Security

	Installed power, MVAr	**Investments, EUR**	**End user electricity price, EUR/MWh**	**TSO service price, EUR/ MVArh**	**Payback time**
Site connected to TSO	–18/+5	379 500	60.89	1.37	25
	–80/+50	2 145 000		1.86	25
	–18/+5	379 500	76.11	1.01	25
	–80/+50	2 145 000		1.39	25
110 kV generator	–18/+5	379 500	60.89	1.37	>25
	–18/+5	379 500	76.11	1.01	>25
330 kV generator	–80/+50	2 145 000	60.89	1.86	>25
	–80/+50	2 145 000	76.11	1.39	>25

5.2. Inertia Provision

Latvian TSO announced necessity of 6000 MWs inertia after synchronization to CEN [22]. Biggest Latvian generators can ensure such amount of inertia only for limited time per year, and average lack of inertia is 2654 MWs.

Inertia could be provided by synchronous compensators (SC) with flywheel, such technology allows to reach inertia constant $H = 8$ s for 200 MVA SC. To ensure the necessary inertia level, 4 SCs should be installed. Flywheels are known for high self-discharge, usually 1–1.7 % per hour [69], [70].

If synchronous compensator with flywheel is used, operating costs can be calculated as follows:

$$C_{\mathrm{oSCa}} = K_{\mathrm{p}} i + K_{\mathrm{p}} k_{\mathrm{m}} + 8760 C_{\mathrm{e}} n_{\mathrm{SC}} \Delta P_{\mathrm{T0}} k_{\mathrm{av}} + C_{\mathrm{e}} \sum_{t=1}^{8760} n_{\mathrm{SC}t} (\Delta P_{\mathrm{SC}} + \Delta P_{\mathrm{T}} + \Delta P_{\mathrm{fw}}), \qquad (5.1)$$

where

C_{oSCa} – yearly operation costs of synchronous compensators with flywheel to provide lacking inertia, EUR;
K_{p} – project capital investments, EUR;
i – credit interest rate, p.u.;
k_{m} – coefficient for maintenance costs per year, p. u.;
ΔP_{T0} – power transformer no-load losses, MW;
k_{av} – availability of technology per year, p. u.;
ΔP_{SC} – synchronous compensator operation losses, MW;
ΔP_{T} – power transformer load losses corresponding to synchronous compensator load, MW;
ΔP_{fw} – flywheel losses, MW;
C_{e} – market based self-consumption electricity costs, EUR/MWh;
$n_{\mathrm{SC}t}$ – number of lacking synchronous compensators at t hour.

The results show that average lack of 2654 MWs of inertia provision will cost 1006.53 EUR per hour at high electricity prices (76.11 EUR/MWh), which is taken as base scenario. Fig. 5.1 shows that the electricity market price has a huge impact on the costs of inertia provided by CCGTs. At high electricity prices generators can provide lower inertia costs, but if low price (60.89 EUR/MWh) scenario appears, generators could not compete with SCs.

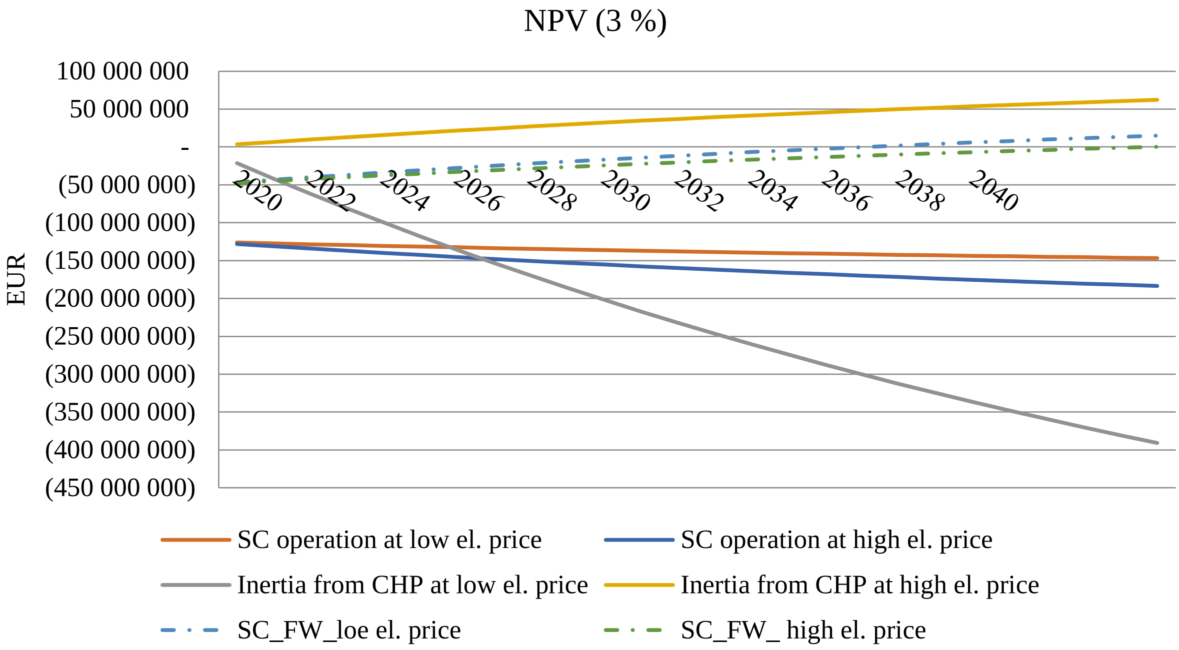

Fig. 5.1. NPV calculation for possible solutions inertia provision.

5.3. Frequency Contamination Reserves

Full activation of FCR should be within 0–30 seconds and be available for at least 15 minutes. In average, biggest generators in Latvia could not provide FCR for 2400 hours per year. To ensure FCR provision for a whole year, BESS could be installed at a TSO connected site or at power plant.

The BESS upkeep costs for a TSO connected site are calculated as follows:

$$C_{\mathrm{up.sub}} = K_{\mathrm{p}} i + K_{\mathrm{p}} k_{\mathrm{m}} + C_{\mathrm{e}}(8760 k_{\mathrm{av}} P_{\mathrm{bs}} + 12 A_{\mathrm{B.f}} k), \tag{5.2}$$

where

$C_{\mathrm{up.sub}}$ – total upkeep costs at the site connected to TSO, EUR;

P_{bs} – power used for BESS upkeep, MW;

$A_{\mathrm{B.f}}$ – BESS capacity for FCR provision, MWh;

k – coefficient that considers self-discharge in BESS, value used for calculation is 0.07.

Hourly additional energy should be purchased to ensure operation of the system:

$$A_{\mathrm{op.f}} = \frac{\Delta P_{\mathrm{f.op}}}{\eta_{\mathrm{op.l}}} t_{\mathrm{op.f}}, \tag{5.3}$$

where

$A_{\mathrm{op.f}}$ – energy purchased for operation in FCR mode, MWh;

$P_{\mathrm{f.op}}$ – average operating power of BESS for FCR provision, MW

$\eta_{\mathrm{op.l}}$ – inverter efficiency operating at a lower than rated power;

$t_{\mathrm{op.f}}$ – time per year when BESS operates in FCR mode, h.

So total costs of FCR provision are:

$$C_{\mathrm{r.op}} = C_{\mathrm{up.sub}} + C_{\mathrm{e}} A_{\mathrm{op.f}}, \tag{5.4}$$

where $C_{\mathrm{r.op}}$ are total yearly operation costs of BESS for FCR provision, EUR.

In the case when BESS is installed and runs at the generator site, C_{e} in (5.2) and (5.4) should be substituted with $C_{\mathrm{el.pp}}$ – yearly average power plant self-consumption electricity costs. Calculations are made for several electricity market price scenarios, assuming operation life of BESS as 10 years. Due to 2 % time for maintenance each year, BESS could not provide FCR all year long. The results are presented in Table 5.2. An alternative is to install a smaller BESS at Riga TEC-1, which would allow biggest Latvian generators fully cover the necessity of FCR. The results are presented in

Table 5.3. If FCR market is open, then none of stand-alone BESS solutions can compete with Riga TEC-1 upgrade and service provision from all biggest generators. It appears due to lower investments and operation costs.

Table 5.2

Costs of FCR if Generators are not Performing in Service Provision

Scenario	**End user electricity price, EUR/MWh**	**Operating hour per year, h**	**Cost per MW per operation hour, EUR/MW per h**
BESS at site connected to TSO. No EU funding.	76.11	8585	10.73
	60.89	8585	9.93
BESS at generator site. No EU funding.	76.11	8585	9.67
	60.89	8585	8.87
BESS at site connected to TSO. 75 % EU funded. FCR is market based (BESS operates 2400 h)	76.11	2400	20.93
	60.89	2400	18.46
BESS at generator site. 75 % EU funding. FCR is market based (BESS operates 2400 h)	76.11	2400	17.60
	60.89	2400	15.53

Table 5.3

Costs of FCR if Generators Perform in Service Provision to 100 %

Scenario	**End user electricity price, EUR/MWh**	**Additional operating costs due to CCGT operation per year, EUR**	**Cost per MW per operation hour, EUR/MW per h**
Riga TEC-1 upgraded with BESS. No EU funding.	76.11	100 320	7.27
	60.89	321 507	8.47

6. CCGT SEFLF-CONSUMPTION MODERNIZATION

PV installation and BESS usage are reported in [29], [73] as a measure to move towards zero-emission buildings, which should work for CCGT self-consumption needs as well. In [30] such solutions are reported as cost effective, it was in Australia. Therefore, [74] reports that Latvia has the lowest PV usage in the Baltic States.

At Riga TEC-2 several PV systems (1 phase 4.6 kW and two 3 phase 13.7 kW each) were installed, the results of 3-year operation and usage for CCGT self-consumption needs show the possibility to reduce finances used for electricity purchase. Basing on data from the installed PV system calculations for bigger systems are made in this Doctoral Thesis in order to find the most economically feasible size of PV system for CCGT self-consumption coverage. Calculation methodology, which considers power plant self-consumption electricity price changes depending on operation mode, as well as the results of program calculation are presented [75].

Another possibility to reduce the costs of self-consumption is to use BESS for peak price shaving, such solution is proposed in [72]. A more advanced solution is to use BESS for PV energy storage, CCGT generated energy storage, and for peak price shaving, which is discussed further. Previously mentioned methodology was enhanced to optimize PV and BESS usage depending on CCGT operating mode to ensure the lowest self-consumption costs. Both developed methodologies were approved on historical data of real CCGTs and electricity market prices.

6.1. PV Generation for Self-Consumption Needs

Data from PV installation deployed at Riga TEC-2 were used to calculate hourly solar irradiation obtained by one solar panel. For any new system specific power for one panel can be calculated from hourly solar irradiation. Any new installation will consist of PV modules of one type and of the same size, calculation of area of all modules should be done, then, (6.1) should be used to calculate total generation of PV system at desired hour.

$$P_{\mathrm{PV}.t} = P_{\mathrm{sp}.t} S_{\mathrm{inst.n}}, \tag{6.1}$$

where

$P_{\mathrm{PV}.t}$ – new PV installation generated power after inverter at hour *t*, kW;

$P_{\mathrm{sp}.t}$ – specific PV power at hour *t*, kW/m^2;

$S_{\mathrm{inst.n}}$ – total area of all new installed PV panels, m^2.

Power from PV system at hour *t* is calculated as

$$\begin{cases} P_{\mathrm{s}.t} = P_{\mathrm{PV}.t} - \Delta P_{\mathrm{inv}.t} - \Delta P_{\mathrm{T}.t} - \Delta P_{\mathrm{c}.t}; \\ P_{\mathrm{PV}.t} - \Delta P_{\mathrm{inv}.t} - \Delta P_{\mathrm{T}.t} - \Delta P_{\mathrm{c}.t} < 0 \ \rightarrow \ P_{\mathrm{s}.t} = P_{\mathrm{PV}.t} - \Delta P_{\mathrm{inv}.t}, \end{cases} \tag{6.2}$$

where

$P_{\mathrm{s}.t}$ – total provided solar power at t hours, kW;

$\Delta P_{\mathrm{inv}.t}$ – losses in inverter at hour *t*, kW;

$\Delta P_{\mathrm{T}.t}$ – power transformer losses at hour *t*, kW;

$\Delta P_{\mathrm{c}.t}$ – losses in medium voltage cables at hour *t*, kW.

Optimal use of solar energy in power plant self-consumption is achieved when function (6.3) is minimized:

$$\begin{cases} f(R) = \sum_{t=1}^{t} (C_{\mathrm{m}.t}(A_{\mathrm{g}.t} - A_{\mathrm{d}.t}) + C_{\mathrm{sc}.t}A_{\mathrm{c}.t} - C_{\mathrm{s}.t}A_{s.t}); \\ A_{\mathrm{c}.t} - A_{\mathrm{s}.t} < 0 \ \rightarrow \ C_{\mathrm{s}.t}A_{\mathrm{s}.t} = C_{\mathrm{sc}.t}A_{\mathrm{c}.t} + C_{\mathrm{m}.t}(A_{\mathrm{s}.t} - A_{\mathrm{c}.t}); \\ A_{\mathrm{c}.t} = 0 \rightarrow \ C_{\mathrm{s}.t}A_{\mathrm{s}.t} = C_{\mathrm{m}.t}A_{\mathrm{s}.t}; \\ A_{\mathrm{c}.t} - A_{\mathrm{s}.t} > 0 \ \rightarrow \ C_{\mathrm{s}.t}A_{\mathrm{s}.t} = C_{\mathrm{sc}.t}A_{\mathrm{s}.t}, \end{cases} \tag{6.3}$$

where

$C_{\mathrm{m}.t}$ – Nord Pool spot market price at *t* hour, EUR/MWh;

$A_{\mathrm{g}.t}$ – power plant generated energy at *t* hour, MWh;

$A_{\mathrm{d}.t}$ – power plant delivered to the grid energy at *t* hour, MWh;

$C_{\mathrm{sc}.t}$ – self-consumption electricity price at *t* hour, EUR/MWh;

$A_{\mathrm{c}.t}$ – power plant consumed from the grid energy at *t* hour, MWh;

$C_{\mathrm{s}.t}$ – PV system generated electricity price at *t* hour, EUR/MWh;

$A_{\mathrm{s}.t}$ – PV system generated energy at *t* hour, MWh;

During the power plant shut-down and startups energy is consumed from the grid and is used for self-consumption. PV produced energy is used to cover self-consumption needs. In case the generated solar energy is greater than self-consumption of power plant, it is sold in electricity market. When the generator operates and does not consume any energy from the grid ($A_{\mathrm{c}.t} = 0$), the energy provided from PV system is priced as market price, because it just allows the generator to deliver more energy to market. When the generator is shut down and PV generation is lower than self-consumption ($A_{\mathrm{s}.t} < A_{\mathrm{c}.t}$), PV generated energy is priced as self-consumption energy from the grid, because it compensates the price which could be paid. But if PV generation is higher than the consumed power from the grid ($A_{\mathrm{s}.t} > A_{\mathrm{c}.t}$), part of generation is at the price of self-consumption electricity, and part is at market price. It means that function component $C_{\mathrm{s}.t}A_{\mathrm{s}.t}$ can change hour to hour.

It is obvious that when installing more powerful PV system solar generation will rise and, as a result from (6.3), will decrease. But the increase of PV system does not always lead to better economic performance. So, results of (6.3) are used in NPV calculation module.

A special program was developed to deal with (6.3) and NPV calculation. Input data are presented in Table 6.1 but calculation algorithm in Fig. 6.1. For NPV calculation it is essential to know investments and predicted revenue, which is calculated in module that solves (6.3). Basing on solar generation, avoided CO_2 emissions are calculated. Revenue from CO_2 certificates is calculated in NPV module.

Table 6.1

Inputs for Calculation

Designation	**Units**	**Description**
A_g	kWh	Power plant generated energy
A_d	kWh	Power plant delivered energy to the grid
A_c	kWh	Power plant consumed energy from the grid
C_m	EUR/MWh	Nord Pool spot market price
C_g	EUR/MWh	Clean energy component (set as 22.68 EUR/MWh)
C_{TSO}	EUR/MWh	Transmission system operator tariff (set as 3.53 EUR/MWh)
n	–	Amount of installed PV panels
S_{PV}	m^2	Total area of one installed PV panel
η_{inst}	p. u.	Installed PV panel efficiency
I	kW/m^2	Solar irradiation
$P_{inv.r}$	kW	PV inverter rated power
k_{ic}	p. u.	PV inverter control self-consumption
k_c	p. u.	Losses in power cables
S_T	kVA	Power transformer apparent power
ΔP_{T0}	kW	Power transformer no-load losses
P_{Tk}	kW	Power transformer load losses
$\cos\varphi$	–	Power factor for power delivered from PV inverter to consumption
m_{CO2}	t/kWh	Avoided CO_2 emissions

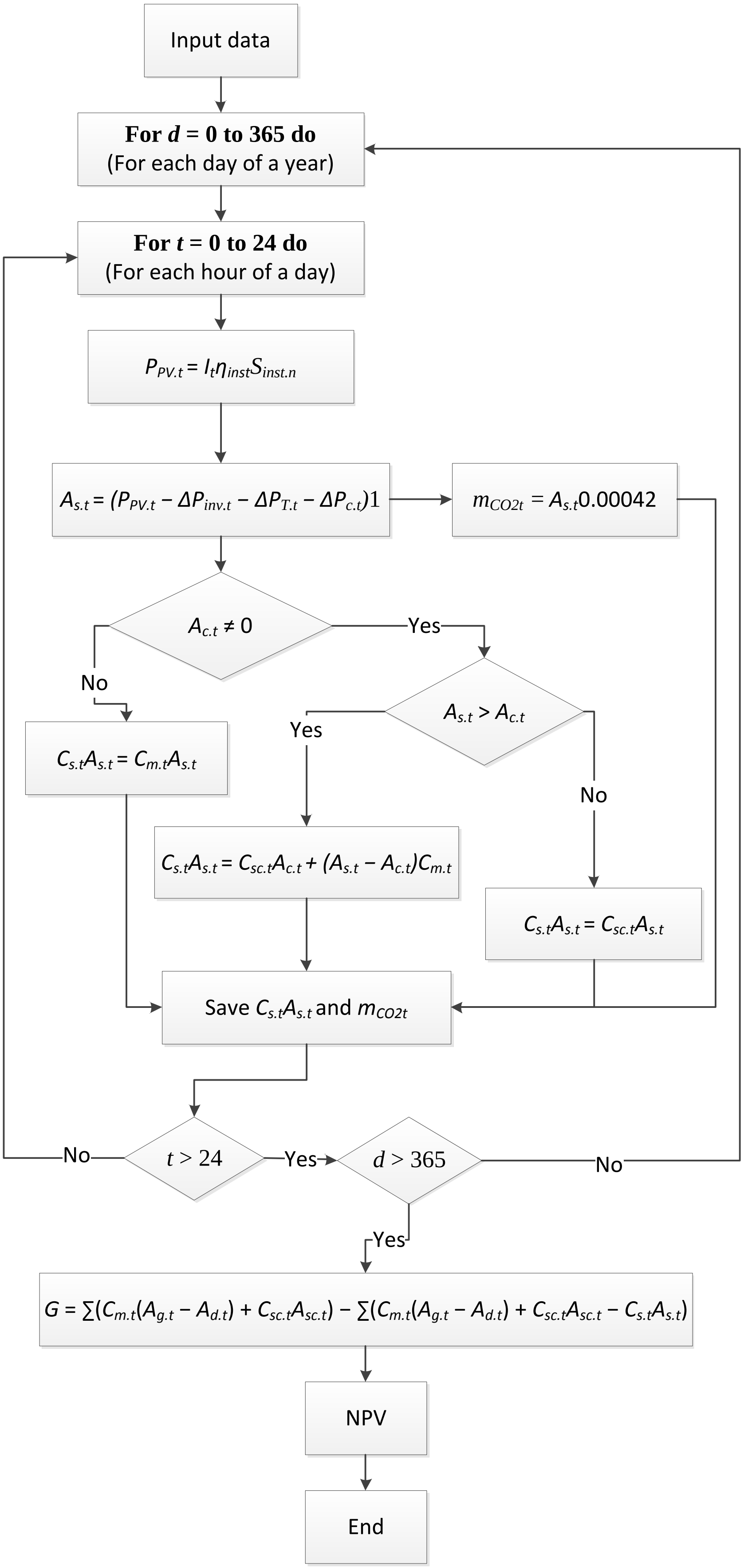

Fig. 6.1. Algorithm to calculate PV generation gain (G) for self-consumption use.

6.2. Use of Battery Storage System for Self-Consumption Needs

Algorithm presented in Fig. 6.1 was modernized by the part presented in Fig. 6.2. This program allows to use battery in various ways.

As the only controllable variable for algorithm is BESS available capacity, the algorithm uses enumeration to find the best hours for BESS discharge and charge from the power grid/generators in case PV generation is not enough.

Target Function (6.3) is changed to

$$\begin{cases} f(R) = \sum_{t=1}^{t} (C_{\mathrm{m}.t}(A_{\mathrm{g}.t} - A_{\mathrm{d}.t}) + C_{\mathrm{sc}.t}A_{\mathrm{c}.t} - C_{\mathrm{s}.t}A_{\mathrm{s}.t} + C_{\mathrm{bs}.t}A_{\mathrm{bs}.t} + C_{\mathrm{BESSc}.t}A_{\mathrm{bc}.t} - C_{\mathrm{BESSd}.t}A_{\mathrm{bd}.t})\,; \\ A_{\mathrm{c}.t} - A_{\mathrm{s}.t} < 0 \;\rightarrow\; C_{\mathrm{s}.t}A_{\mathrm{s}.t} = C_{\mathrm{sc}.t}A_{\mathrm{c}.t}; \\ A_{\mathrm{c}.t} = 0;\; A_{\mathrm{g}.t} - A_{\mathrm{d}.t} - A_{\mathrm{s}.t} < 0 \rightarrow\; C_{\mathrm{s}.t}A_{\mathrm{s}.t} = C_{\mathrm{m}.t}A_{\mathrm{s}.t};\; C_{\mathrm{BESSc}} = 0; \\ A_{\mathrm{c}.t} = 0; A_{\mathrm{g}.t} - A_{\mathrm{d}.t} - A_{\mathrm{s}.t} > 0 \rightarrow\; C_{\mathrm{s}.t}A_{\mathrm{s}.t} = C_{\mathrm{m}.t}A_{\mathrm{s}.t};\; C_{\mathrm{BESSc}.t} = C_{\mathrm{m}.t};\; C_{\mathrm{bs}.t} = C_{\mathrm{m}.t}; \\ A_{\mathrm{c}.t} - A_{\mathrm{s}.t} > 0 \;\rightarrow\; C_{\mathrm{s}.t}A_{\mathrm{s}.t} = C_{\mathrm{sc}.t}A_{\mathrm{s}.t};\; C_{\mathrm{BESSd}.t} = C_{\mathrm{sc}.t};\; A_{\mathrm{bd}.t} \leq A_{\mathrm{c}.t} - A_{\mathrm{s}.t}; \\ A_{c.t} > 0 \rightarrow C_{bs.t} = C_{sc.t}; \\ t_{\mathrm{BESSc}} \neq t_{\mathrm{BESSd}}, \end{cases} \tag{6.4}$$

where

$C_{\mathrm{BESSc}.t}$ – BESS charging price at hour *t*, EUR/MWh;
$C_{\mathrm{BESSd}.t}$ – BESS discharging price at hour *t*, EUR/MWh;
$C_{\mathrm{bs}.t}$ – BESS no load self-consumption price at hour *t*, EUR/MWh;
$A_{\mathrm{bc}.t}$ – energy amount that is used for battery charging at hour *t*, MWh;
$A_{\mathrm{bc}.t}$ – energy amount that is discharged from battery at hour *t*, MWh;
$A_{\mathrm{bs}.t}$ – energy amount used for BESS no-load losses at hour *t*, MWh;
t_{BESSc} – hour when BESS charging could be made;
t_{BESSd} – hour when BESS discharging could be made.

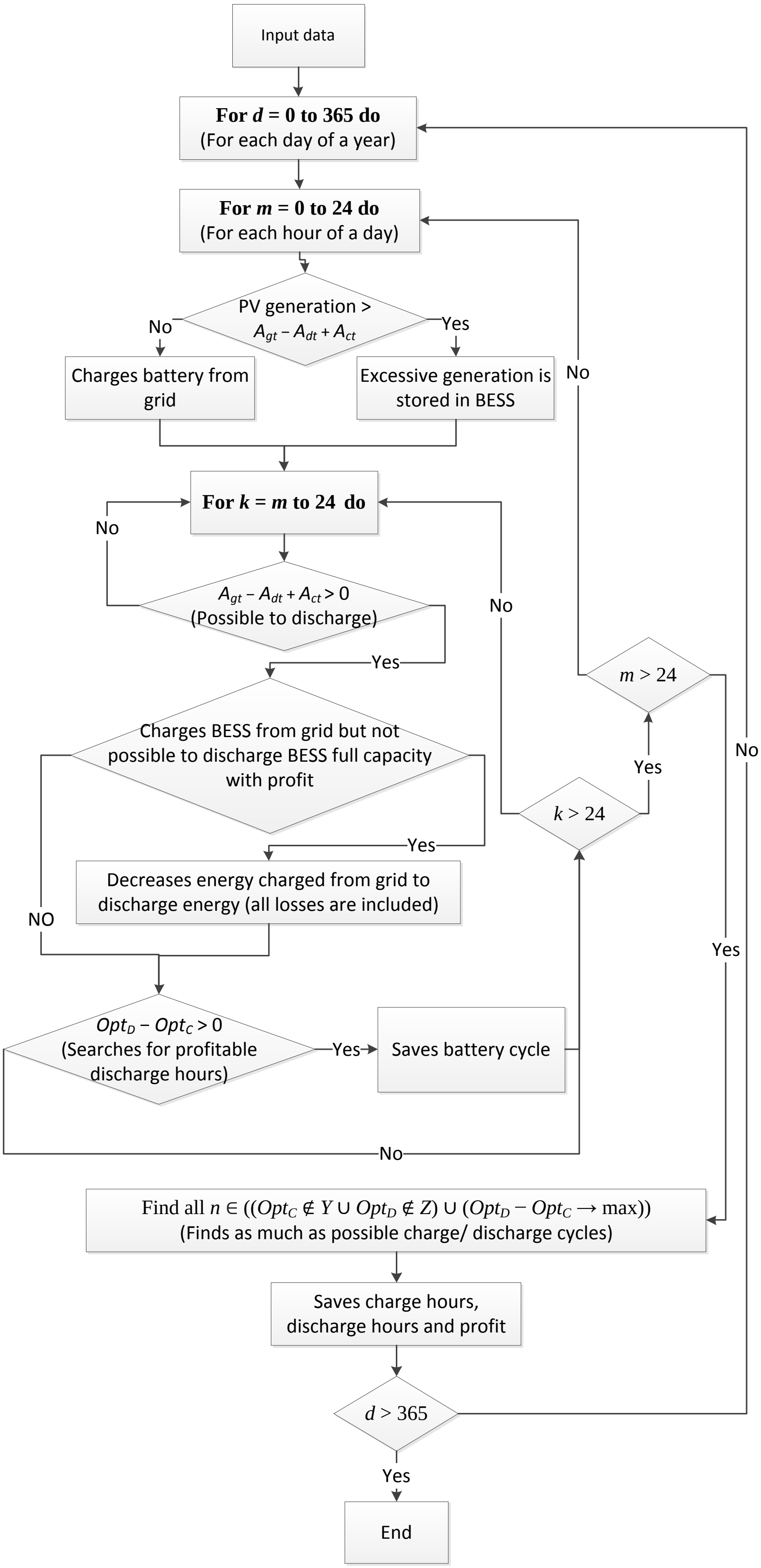

Fig. 6.2. Algorithm for BESS profit calculation for CCGT self-consumption use.

Opt – function optimum for *f*(R), with related hourly energy consumption; $\mathrm{Opt_C}$ – function optimum for *f*(PC), with related battery charging hours; $\mathrm{Opt_D}$ – function optimum for *f*(PD), with related battery discharging hours; *Y* – hours when charging is not possible; *Z* – hours when discharging is not possible.

In winter days (Fig. 6.3), when no PV generation is present, the price difference was used, charging BESS during cheaper hours (1, 2, and 3) and discharging during high price hours (7 and 8). To gain maximum profit from such operation, part of the charged energy was discharged only in the 17th hour, when the revenue was higher than in any previous or upcoming hour, taking into account BESS losses.

During the day with PV generation (Fig. 6.4) the main task was to store all excessive PV generation and later use it for self-consumption needs. The developed algorithm correctly charged BESS during all hours when PV generation exceeded self-consumption needs. At the 19th and 20th hour BESS started discharging and the covered amount of energy solar generation was not providing self-consumption needs. At the 23rd hour the price was slightly lower than at the 24th hour and BESS was not discharging at the 23rd hour to make maximal profit in this day.

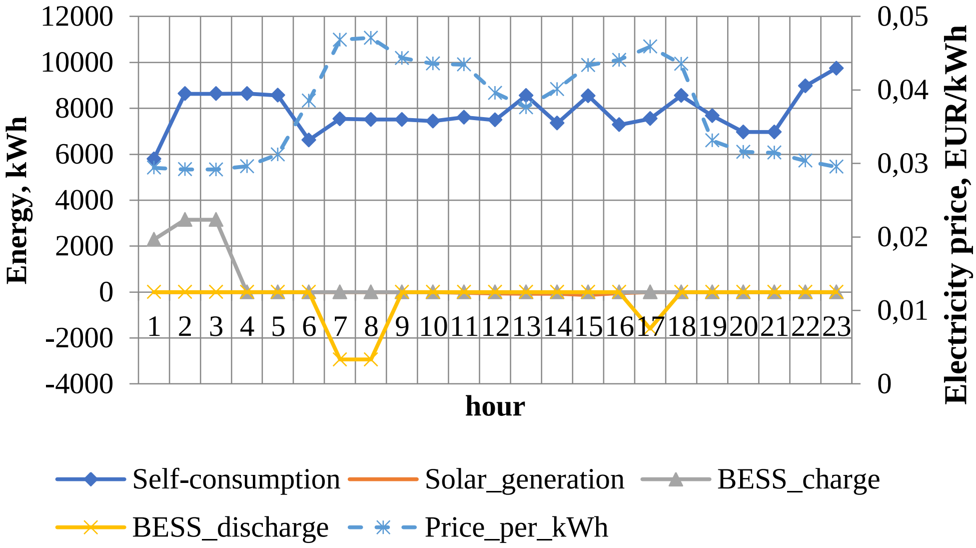

Fig. 6.3. BESS optimal charging and discharging during the day without PV generation.

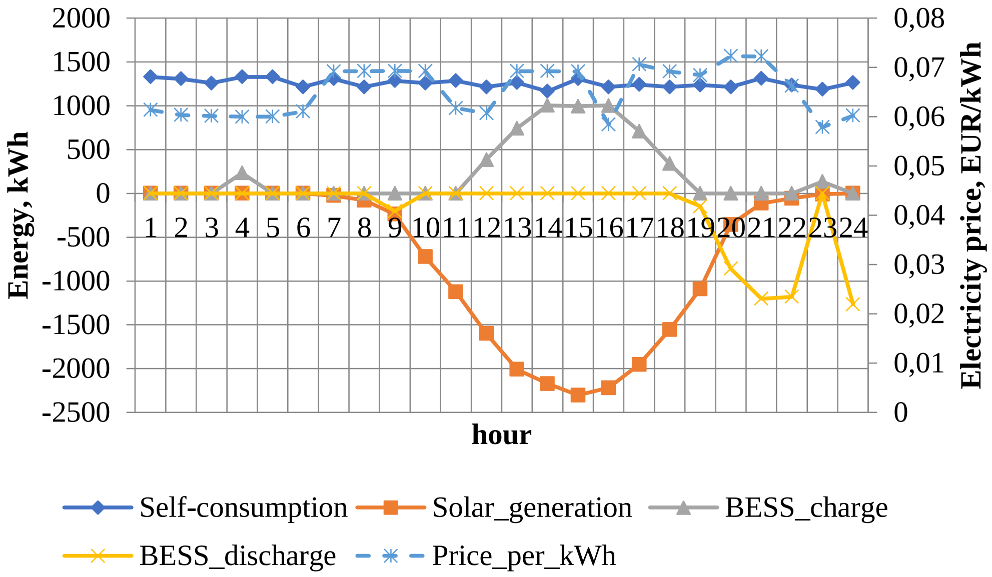

Fig. 6.4. BESS optimal charging and discharging during the day with PV generation.

Results of economic calculations are presented in Table 6.2. Data is represented for a CCGT plant with low generation in summer during the year with higher electricity prices and solar generation, which is most optimistic scenario. Revenue from stabilized CO_2 allowance price was considered.

Table 6.2

Comparison of Revenues From PV System and PV System With BESS

	Income from system operation, EUR	**Maintenance and no-load self-consumption per year, EUR**	**Revenue per year considering operation and no-load losses, EUR**	**% of PV revenue**
PV 1425 kW	97 940.85	11 307.12	86 633.73	100
PV 1425 kW, 1500 kWh BESS	113 318.55	58 776.70	54 541.85	62.96
PV 1425 kW, 3000 kWh BESS	123 706.18	62 226.70	61 479.49	70.966
PV 1852 kW	121 290.32	14 688.45	106 601.87	100
PV 1852 kW, 2000 kWh BESS	145 940.23	74 312.93	71 627.30	67.19
PV 1852 kW, 4000 kWh BESS	158 714.38	78 912.93	79 801.45	74.86
PV 2565 kW	151837.10	20 324.01	131 513.09	100
PV 2565 kW, 4000 kWh BESS	205 697.16	116 187.55	89 509.60	68.06
PV 2565 kW, 8000 kWh BESS	222 321.86	125 387.56	96 934.30	73.71

Using the combination of excessive solar system and BESS leads to much higher investments, BESS installation costs are significant, but even more problems arise from no-load losses of battery storage system. At present such solution is not feasible and installation of PV system without BESS is preferable.

7. OUTAGE AND ANCILLARY SERVICE IMPACT ON CCGT OPERATION STRATEGY

The proposed methodology is presented in Fig. 7.1. Several steps should be taken before impact calculation. Service prices that should be used are presented in Table 7.1. Step four is simulation allowing to understand weather additional income from ancillary service provision allows to reduce the number of startups and/or shutdowns in order to reduce the incident rate of CCGT electrical equipment, unavailability time, and caused costs. Step five is the analysis of simulation in which λ, k_{un} of power plant electrical equipment and caused costs are recalculated according to simulation results and compared to the results before simulation.

Table 7.1

Amount and Costs of Ancillary Service

Service	**Amount per hour (average per year)**	**Generator price for service**	**Price of equipment connected to TSO for service**
Reactive power control	–64 MVAr	$C_{\mathrm{qm.sub}}$	$C_{\mathrm{qm.sub}}$
Inertia	2200 MWs	$\frac{E_{\mathrm{CHP}}C_{\mathrm{i}}}{E_{\mathrm{h}}}$	C_{i}
FCR	15 MW / 15 min	$C_{\mathrm{F.g}} = \frac{C_{\mathrm{up.gen}}}{t_{\mathrm{op}}}$	$C_{\mathrm{F.sub}} = \frac{C_{\mathrm{r.op}}}{t_{\mathrm{op}}}$

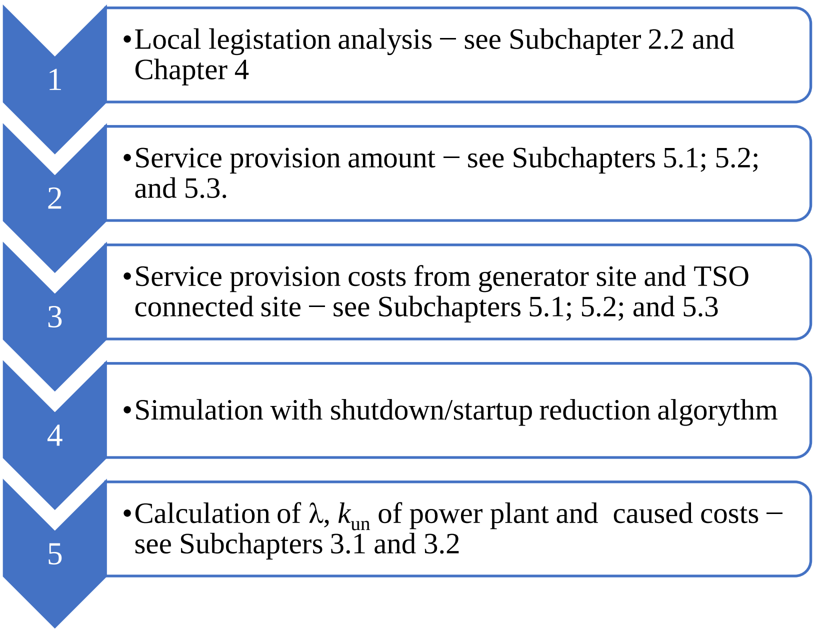

Fig. 7.1. Methodology of outage and ancillary service provision impact analysis.

7.1. Reduction of Number of Cycles and Profit Maximization Algorithms

Optimization of CCGT operation, e.g. increase of flexibility, reduction of operation and startup costs are presented in various publications [3], [6], [7], [33]. Provision of ancillary service could open new possibilities for flexibility improvement, due to additional income. Proposed methodology takes into account reduction of costs due to change of startup type, which is described in [40].

For the proposed methodology power plant operation was divided into three stages, startup, operation mode, and shutdown. The idea is to extend operating hours moving the startups back in time or shutdown forward. The assumption is made, that such movement does not impact market electricity price. Service provision is taken as additional income. Moving startup and shutdown hours sometimes leads to power generation in hours when market electricity prices are lower than electricity production costs. As additional income from movement reduction of startup costs is taken.

The program based on the proposed methodology is developed to solve two tasks; the first one is maximization of power plant profit. As moving is related to loss of income from electricity trading and program seeks to make any change only if some profit from startup costs reduction and service provision is foreseen. The second task is defined as reduction of number of startup, for this reason program uses all income from service provision in normal operating mode to cover the losses of electricity trading when power plant is not originally operated. The parameters given in Table 7.2 are used.

Table 7.2

Parameters for Shutdown/Startup Reduction Algorithm Simulation

Designation	Description
t	Time, h
t_{st}^{n-1}	Hour of previous shutdown, h
t_{st}^{n}	Hour of actual startup, h
$P_{\mathrm{st.1}}, P_{\mathrm{st.2}}, \dots, P_{\mathrm{st.}k}$	Active power of 1st , 2nd … kth hour of startup sequence, MW
k	Startup sequence duration
P_{min}	Generator minimum allowed active power, MW
$Q_{\mathrm{st.1}}, Q_{\mathrm{st.2}}, \dots, Q_{\mathrm{st.}k}$	Reactive power of 1st , 2nd … kth hour of startup sequence, MVAr
Q_{avg}	Average reactive power provided from generator site, MVAr
C_t	Electricity market price at hour t, EUR/MWh
$C_{\mathrm{st.1}}, C_{\mathrm{st.2}}, \dots, C_{\mathrm{st.}k}$	Electricity market price of 1st , 2nd … kth hour of startup sequence, EUR/MWh
C_0	Active power generation costs, EUR/MWh
C_{q}	Price for generated reactive power, EUR/MVArh
C_{i}	Price for generator provided inertia, EUR/MWs
E_{CHP}	Generator provided inertia, MWs
$C_{\mathrm{F.g}}$	Price of generator granted FCR of 15 MW for 15 minutes
$P_{\mathrm{sp.1}}, P_{\mathrm{sp.2}}, \dots, P_{\mathrm{sp.}m}$	Active power of 1st , 2nd … mth hour of shutdown sequence, MW
$Q_{\mathrm{sp.1}}, Q_{\mathrm{sp.2}}, \dots, Q_{\mathrm{sp.}m}$	Reactive power of 1st , 2nd … mth hour of shutdown sequence, MVAr
$C_{\mathrm{sp.1}}, C_{\mathrm{sp.2,}}, \dots, C_{\mathrm{sp.}m}$	Electricity market price of 1st , 2nd … mth hour of startup sequence, EUR/MWh
m	Shutdown sequence duration

Continuation of Table 7.3

C_s	Avoided costs of startup due to change of state of startup (cold/warm/hot), EUR
$t_\mathrm{sp.s}$; $t_\mathrm{st.s}$	Hours of simulated shutdown and startup
n	Iteration number

Function for simulated startup hours is expressed as follows:

$$f_1 = \sum_{t=t_{\mathrm{st}}^{n}-1}^{t=t_{\mathrm{sp}}^{n-1}+1} \left[P_{\mathrm{st.1}}(C_t - C_{\mathrm{st.1}}) + Q_{\mathrm{st.1}}C_\mathrm{q} + P_{\mathrm{st.2}}(C_{t+1} - C_{\mathrm{st.2}}) + Q_{\mathrm{st.2}}C_\mathrm{q} + \cdots \right. \\ \left. + P_{\mathrm{st.}k}(C_{t+k} - C_{\mathrm{s.}k}) + Q_{\mathrm{st.}k}C_\mathrm{q}\right] + k\frac{E_\mathrm{CHP}C_\mathrm{i}}{E_\mathrm{h}}. \tag{7.1}$$

Function for simulated hours between real operating hours and simulated startup hours is expressed as

$$f_2 = \sum_{t=t_{\mathrm{st}}^{n}}^{t=t_{\mathrm{sp}}^{n-1}+k+1} \left[P_\mathrm{min}(C_t - C_0) + \frac{E_\mathrm{CHP}C_\mathrm{i}}{E_\mathrm{h}} + Q_\mathrm{avg}C_\mathrm{q} + C_\mathrm{F.g}\right]. \tag{7.2}$$

Function for simulated shutdown hours is expressed as follows:

$$f_3 = \sum_{t=t_{\mathrm{sp}}^{n-1}+1}^{t=t_{\mathrm{st}}^{n}-m} \left[P_{\mathrm{sp.1}}(C_t - C_{\mathrm{sp.1}}) + Q_{\mathrm{sp.1}}C_\mathrm{q} + P_{\mathrm{sp.2}}(C_{t+1} - C_{\mathrm{sp.2}}) + Q_{\mathrm{sp.2}}C_\mathrm{q} + \cdots \right. \\ \left. + P_{\mathrm{sp.}m}(C_{t+m-1} - C_{\mathrm{sp.}m}) + Q_{\mathrm{sp.}m}C_\mathrm{q}\right] + m\frac{E_\mathrm{CHP}C_\mathrm{i}}{E_\mathrm{h}}. \tag{7.3}$$

Function for simulated hours between real operating hours and simulated shutdown hours is expressed as

$$f_4 = \sum_{t=t_{\mathrm{sp}}^{n-1}}^{t=t_{\mathrm{st}}^{n}-m-1} \left[P_\mathrm{min}(C_t - C_0) + \frac{E_\mathrm{CHP}C_\mathrm{i}}{E_\mathrm{h}} + Q_\mathrm{avg}C_\mathrm{q} + C_\mathrm{F.g}\right]. \tag{7.4}$$

Function of additional profit from ancillary service provision for operating hours is expressed as

$$f_5 = \sum_{t=t_{\mathrm{sp}}^{n}}^{t=t_{\mathrm{st}}^{n}} \left(\frac{E_\mathrm{CHP}C_\mathrm{i}}{E_\mathrm{h}} + Q_\mathrm{avg}C_\mathrm{q} + C_\mathrm{F.g}\right). \tag{7.5}$$

To ensure maximal profit gained from ancillary service provision, the following function is proposed:

$$\begin{cases} Y_{\mathrm{mp}}^{n} = f_1^n + f_2^n + f_3^{n-1} + f_4^{n-1} + C_{\mathrm{s}}; \\ 8 < t_{\mathrm{st}}^{n} - t_{\mathrm{sp}}^{n-1} \leq 72;\ t_{\mathrm{st.s}}^{n} - t_{\mathrm{sp.s}}^{n-1} \leq 8\ \rightarrow C_{\mathrm{sh}} = 16\,020; \\ 72 < t_{\mathrm{st}}^{n} - t_{\mathrm{sp}}^{n-1};\ t_{\mathrm{st.s}}^{n} - t_{\mathrm{sp.s}}^{n-1} \leq 8\ \rightarrow C_{\mathrm{s}} = 29\,380; \\ 72 < t_{\mathrm{st}}^{n} - t_{\mathrm{sp}}^{n-1};\ 8 < t_{\mathrm{st.s}}^{n} - t_{\mathrm{sp.s}}^{n-1} \leq 72\ \rightarrow C_{\mathrm{s}} = 13\,360; \\ t_{\mathrm{st.s}}^{n} - t_{\mathrm{sp.s}}^{n-1} > 72\ \rightarrow C_{\mathrm{s}} = 0; \\ 0 < t_{\mathrm{st}}^{n} - t_{\mathrm{sp}}^{n-1} \leq 8;\ t_{\mathrm{st.s}}^{n} - t_{\mathrm{sp.s}}^{n-1} = 0\ \rightarrow C_{\mathrm{s}} = 16\,020. \end{cases} \tag{7.6}$$

To ensure the least number of startups using gain from ancillary service provision, the following function is proposed:

$$\begin{cases} Y_{\mathrm{lst}}^{n} = f_1^n + f_2^n + f_5^n + f_3^{n-1} + f_4^{n-1} + C_{\mathrm{s}}; \\ 8 < t_{\mathrm{st}}^{n} - t_{\mathrm{sp}}^{n-1} < 72;\ t_{\mathrm{st.s}}^{n} - t_{\mathrm{sp.s}}^{n-1} \leq 8\ \rightarrow C_{\mathrm{sh}} = 16\,020; \\ 72 < t_{\mathrm{st}}^{n} - t_{\mathrm{sp}}^{n-1};\ t_{\mathrm{st.s}}^{n} - t_{\mathrm{sp.s}}^{n-1} \leq 8\ \rightarrow C_{\mathrm{s}} = 29\,380; \\ 72 < t_{\mathrm{st}}^{n} - t_{\mathrm{sp}}^{n-1};\ 8 < t_{\mathrm{st.s}}^{n} - t_{\mathrm{sp.s}}^{n-1} \leq 72\ \rightarrow C_{\mathrm{s}} = 13\,360; \\ t_{\mathrm{st.s}}^{n} - t_{\mathrm{sp.s}}^{n-1} > 72\ \rightarrow C_{\mathrm{s}} = 0; \\ 0 < t_{\mathrm{st}}^{n} - t_{\mathrm{sp}}^{n-1} \leq 8;\ t_{\mathrm{st.s}}^{n} - t_{\mathrm{sp.s}}^{n-1} = 0\ \rightarrow C_{\mathrm{s}} = 16\,020. \end{cases} \tag{7.7}$$

In Fig. 7.2 graphical presentation of (7.7) is provided. Functions (7.6) and (7.7) include avoided costs due to better startup position, for example, moving from cold start state to hot start state will allow to avoid the costs of 29 380 EUR and in Y function are included as additional profit. Prices of possible avoided costs of different startup states were calculated from data provided in [40] for a similar 400 MW CCGT power plant.

When maximizing income of CCGT, the main objective of program is defined as

$$\sum_{n=0}^{n} Y_{\mathrm{mp}}^{n} \rightarrow \max. \tag{7.8}$$

When moving to reduction of number of CCGT startup, the main objective of program is defined as

$$\begin{cases} \displaystyle\sum_{n=0}^{n} Y_{\mathrm{lst}}^{n} > 0; \\ \displaystyle\sum_{n=1}^{n} t_{\mathrm{st.s}}^{n} - t_{\mathrm{sp.s}}^{n-1} \rightarrow \min. \end{cases} \tag{7.9}$$

Historical data of real 400 MW CCGT as well as methodology calculation results for 400 MW CCGT running in 2017, when there was the lowest electricity market price in Latvia, are provided in

Table 7.4; the same for 2018, when there was the highest market electricity price in Latvia, is provided in Table 7.5. Calculation of generator incident rate, total incident rate, and caused unavailability was done as described in Subchapter 3.1, the costs of incidents and caused unavailability were calculated as defined in Subchapter 3.2. Results show, that steering for maximum profit is better in the case of low operating number (2359) of hours and high number (28) of starts, therefore in the case of high operating hours (5421) and the same startup number as previously, seeking for startup number reduction might lead to even better economic gain than seeking for maximal profit. The proposed methodology for power plant planning enhancement could be easily applied to various scenarios and each case should be analyzed separately, no general statement can be made from obtained results.

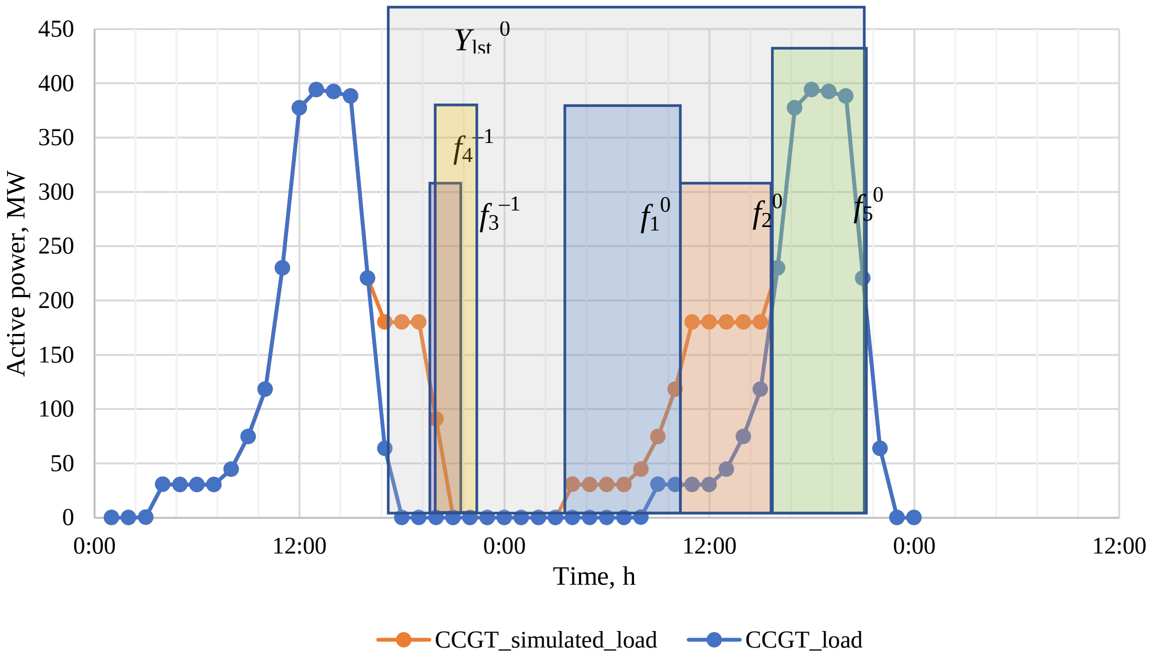

Fig. 7.2. Visualization of algorithm of reduction of shutdown/startup number.

Table 7.4

Results of the Proposed Methodology for 400 MW CCGT for 2017

	Operating hours	**Number of startups**			**Generator incident rate**	**Total incident rate**	**Unavail-ability hours**	**Incident and unavailability caused costs, EUR**	**Profit from ancillary service provision, EUR**	**Total, EUR**
		Hot	**Warm**	**Cold**						
Ancillary service provision	2358	1	8	18	0.366 84	0.385 94	44.03	–1 301 183	2 370 192	1 069 009
Maximum profit after planning enhancement	2479	1	12	13	0.369 92	0.389 02	42.98	–1 277 500	2 586 604	**1 309 104**
Least starts after planning enhancement	2773	0	5	13	0.340 64	0.359 74	33.91	–1 049 080	2 137 948	1 088 868

Table 7.5

Results of the Proposed Methodology for 400 MW CCGT for 2018

	Operating hours	**Number of startups**			**Generator incident rate**	**Total incident rate**	**Unavail-ability hours**	**Incident and unavailability caused costs, EUR**	**Profit from ancillary service provision, EUR**	**Total, EUR**
		Hot	**Warm**	**Cold**						
Ancillary service provision	5421	3	17	8	0.618 48	0.637 58	47.88	–1 508 885	5 652 005	4 143 119
Maximum profit after planning enhancement	6203	2	6	5	0.355 61	0.374 71	31.17	–990 983	7 201 747	6 210 763
Least starts after planning enhancement	6457	0	0	5	0.144 91	0.164 01	20.95	–651 265	6 949 929	**6 298 663**

CONCLUSIONS

1. Analysis of available statistics was made to obtain empirical formulas for incident and unavailability calculations for CHP main electrical equipment. Results show that the rise in number of startups leads to more incidents and unavailability of main electrical equipment, the same is with the rise of operating hours, whereas impact is much lower.
2. Costs of incident caused unavailability were evaluated to show economic impact of main electrical equipment incidents. The obtained results can be used in risk assessment and in future planning of power plant operation.
3. Additional equipment should be installed at existing generator sites to fulfill RfG. In the Doctoral Thesis calculation examples are provided to ensure proper modernization of existing generators. Some cases were analyzed, and solutions were proposed.
4. Synchronization with CEN will lead to new ancillary service markets. For that reason, calculations of costs for reactive power provision, inertia and FCR provision were made. Results show that the lowest rate of reactive power control is possible if generators are not remunerated for service provision. Provision of FCR is cheaper when provided from biggest generators. Inertia provision is the most costly ancillary service, generators should be remunerated for such service provision to reduce investments in installation of additional equipment in power network.
5. Methodology to calculate possible gains from PV system installation for CCGT self-consumption needs was developed. Results show that PV installation is especially useful for power plants with low operating hours in summer. Most optimistic results show payback time of 13 years without any support, thus 0 % interest rate was assumed. The optimal size of installed PV system should be 1 to 1.5 times of minimal summer self-consumption load. The developed program can be applied to any specific case to calculate optimal power of PV system.
6. Combination of oversized PV and BESS does not show any economic gain due to high investments, no-load losses and relatively high losses during operation. The developed methodology for BESS operation optimization for CCGT self-consumption was approved on historical data.
7. The developed methodology for CCGT operation planning enhancement was tested on historical data. It allows to seek for maximal gain from ancillary service provision or minimum startup number per year. Based on the gained results total incident rates as well as caused unavailability costs of generators and main electrical equipment were calculated. Comparing the results of both approaches allow to choose optimal operation strategy for CCGT.
8. CCGTs are capable to provide all necessary services to support grid stability.
   Remuneration of ancillary services will give new possibilities for CCGTs. Methodology for CCGT operation planning enhancement shows that ancillary service provision allows to move to less cycling operation mode.

LITERATURE SOURCES

1. Centrālā statistikas pārvalde https://www.csb.gov.lv
2. T. Makalska, R. Varfolomejeva, R. Oļekšijs, The Impact of Wind Generation on the Spot Market Electricity Pricing // International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), 12−15 June 2018, Palermo, Italy.
3. M. Kunickis, M. Balodis, O. Linkevics and P. Ivanova, "Flexibility options of Riga CHP-2 plant operation under conditions of open electricity market," 2015 IEEE 5th International Conference on Power Engineering, Energy and Electrical Drives (POWERENG), Riga, 2015.
4. Commission Regulation (EU) 2016/631 of 14 April 2016 establishing a network code on requirements for grid connection of generators RfG (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32016R0631).
5. C. H. Lee ; Zainul Asri Mamat, Investigation of Performance Degradation for TNB Newly Commissioned Combined Cycle Power Plant Case study at PD1. // 2009 3rd International Conference on Energy and Environment (ICEE), 7−8 Dec. 2009, Malacca, Malaysia.
6. Gulen, S. C. Gas Turbine Combined Cycle Fast Start: The Physics Behind the Concept // Power engeneering magazine 06.12.2013.
7. Baling, L. Fast cycling and rapid start-up: new generation of plants achieves impressive results // Modern power systems January 2011.
8. M.Baca, Extended requirements on turbogenerators due to changed operational regimes // VGB Congress 2015, Vienna.
9. C. V. Maughan, "Root-cause diagnostics of generator service failures," IEEE International Conference on Electric Machines and Drives, 2005., San Antonio, TX, 2005, pp. 1927−1935.
10. NERC (North American electrical reliability corporation) report "State of reliability 2018" https://www.nerc.com
11. Technical scientific report Analysis of unavailability of power plants 2008-2017 // VGB PowerTech Service GmbH, 2018, Essen, Germany
12. Bruetsch, M., Tari, M., Froehlich, K., Weiers, T., Vogelsang, R. Insulation failure mechanism of power generators // IEEE electrical insulation magazine vol. 24. 2008.
13. Griffith, G., Tucker, S., Milsom, J., Stone, G. Problems with modern air-cooled generator stator winding insulation // IEEE Electrical insulation magazine vol. 16, issue 6, 2000
14. P.J. Tavner and A.F. Anderson Core faults in large generators // IEE Proc.-Electr. Power Appl., Vol. 152, No. 6, November 2005
15. C.V. Maughan "CliffsNotes" on design, O&M of stator-bar insulation systems helps improve reliability. https://www.ccj-online.com/ccj-issue-53/generators-cliffsnotes-on-design-om-of-stator-bar-insulation-systems-helps-improve-reliability/.
16. C. Antoun, High Voltage Circuit Breaker and Power Transformer Failure Modes and Their Detection // 2018 Condition Monitoring and Diagnosis (CMD) 23−26 Sept. 2018, Perth, WA, Australia.

17. L. Chmura, P.H.F. Morshuis, E.Gulski, J.J. Smit, A. Janssen Statistical analysis of subcomponent failures in power transformers // 2011 Electrical Insulation Conference (EIC), 5−8 June 2011, Annapolis, MD, USA.
18. CIGRE Working Group A2.37, “TRANSFORMER RELIABILITY SURVEY,” CIGRE TB 642, Dec. 2015.
19. Technical-Scientific Report. Availability of Power Plants 2005 to 2014 // VGB PowerTech Service GmbH, 2015, Essen, Germany.
20. European solidarity on Energy: Synchronisation of the Baltic States' electricity network with the European system strengthens security of supply, Brussels, 28 June 2018 http://europa.eu/rapid/press-release_IP-18-4284_en.htm
21. R. Oļekšijs and B. Olekshii, “Combined heat and power plant electrical equipment incident rate and unavailability empirical expression,” 2019 IEEE 7th IEEE Workshop on Advances in Information, Electronic and Electrical Engineering (AIEEE)
22. AS Augstsprieguma tīkls http://ast.lv/lv
23. I. Zicmane, K. Berzina, A. Sobolevskis and S. Kovalenko, “Latvian electrical power system stability's analysis taking into account new development strategy until 2025,” 2017 International Conference on Electromechanical and Power Systems (SIELMEN), Iasi, 2017.
24. ENTSO-E https://www.entsoe.eu/
25. K. Marcina, A. Sauhats, V. Lavrinovics and G. Junghans, “Efficiency Analysis of the Baltic Balancing Market,” 2018 15th International Conference on the European Energy Market (EEM), Lodz, 2018.
26. Siemens Siestorage https://fluenceenergy.com/energy-storage-solutions/energy-storage-technology/siestorage-energy-storage/
27. Krickis, O., Oļekšijs, R. Safe operation of the industrial centrifugal pump sets in parallel connection. In: 2017 IEEE 58th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), 12−13 October 2017, Riga, Latvia.
28. Oļekšijs, R., Linkevičs, O. Photovoltaic system application for industry self consumption needs. In: 2018 IEEE 59th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), 12−13 November 2018, Riga, Latvia
29. K. Berzina, I. Zicmane and A. Sobolevskis, Optimal PV electrical energy storage of office building's communal space lighting, // 2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), Milan, 2017, pp. 1−4.
30. P. Sokolowski, W. Peng, R. Patel and X. Yu Roles of Policy Settings in Distributed Generation with Battery Storage // IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society, 29 Oct.−1 Nov. 2017, Beijing, China.
31. Yui. Y. V., Yee Y.V., P. Singh Combined cycle power plant performance degradation // PowerGen Asia, 1998.

32. Zwebek, A., and Pilidis, P. Degradation Effects on Combined Cycle Power Plant Performance—Part I: Gas Turbine Cycle Component Degradation Effects // ASME. J. Eng. Gas Turbines Power. 2003.
33. Kumar, N., Besuner, P.M., Lafton, S.A., Agan, D.D., Hilleman, D.D. Power plant cycling costs // Intertek APTECH, 2012
34. Van den Bergh, K., Delarue, E. Cycling of conventional power plants: technical limits and actual costs // Energy Conversion and Management, Volume 97, pp. 70−77, 2015
35. A. Lisnianski, D. Laredo and H. B. Haim, Multi-state Markov Model for Reliability Analysis of a Combined Cycle Gas Turbine Power Plant // 2016 Second International Symposium on Stochastic Models in Reliability Engineering, Life Science and Operations Management (SMRLO), Beer-Sheva, 2016
36. C. Kirchsteiger, J. Teichmann and L. Balling Probabilistic outage analysis of a combined-cycle power plant // Power Engineering Journal, vol. 9, no. 3, pp. 137−141, 1995.
37. D. C. Montgomery, G. C. Runger Applied statistics and probability for engineers -3rd edition, John Wiley and Sons, 976 p., 2003.
38. L. Ning, W. Wu and B. Zhang Generator random outage model for risk-based monthly maintenance scheduling // 2010 IEEE 11th International Conference on Probabilistic Methods Applied to Power Systems, Singapore, 2010.
39. K. Dahal, K. Al-Arfaj, K. Paudyal Modelling generator maintenance scheduling costs in deregulated power markets // European Journal of Operational Research, Volume 240, Issue 2, 2015.
40. P. Ivanova, O. Linkevics and A. Sauhats, “Mathematical description of combined cycle gas turbine power plants' transient modes,” 2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), Milan, 2017.
41. N. Miller, D. Lew, R. Piwko, L. Hannet, S. Achilles and other Technology capabilities for ast frequency response // GE Energy consulting, 2016.
42. A. Jager- Waldau. JRC Science for policy report. PV status report 2016.
43. N. M. Nor, A. Ali, T. Ibrahim, M. F. Romlie Battery Storage for the Utility-Scale Distributed Photovoltaic Generations // IEEE Access (Volume: 6) 28 November 2017.
44. S. S. Martin, A. Chebak, A. El Ouafi, M. Mabrouki Modeling and Simulation of Hybrid Power System Integrating Wind, Solar, Biodiesel Energies and Storage Battery // 2016 International Renewable and Sustainable Energy Conference (IRSEC), 14−17 Nov. 2016, Marrakech, Morocco.
45. P. Ivanova, A. Sauhats and O. Linkevics, “Towards optimization of combined cycle power plants’ start-ups and shut-down,” 2016 57th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), Riga, 2016.
46. E. David; L. Lamarre “Low-frequency dielectric response of epoxy-mica insulated generator bars during multi-stress aging”// IEEE Transactions on Dielectrics and Electrical Insulation Volume: 14 , Issue: 1, pp. 212-226, Feb. 2007

47. H. MAJCHRZAK, A. CICHOŃ, S. BORUCKI, Application of the Acoustic Emission Method for Diagnosis of On-Load Tap Changer // Archives of acoustics Vol. 42, No. 1, pp. 29–35, 2017.
48. V. Behjat, A. Vahedi, A. Setayeshmehr, H. Borsi, and E. Gockenbach, Diagnosing Shorted Turns on the Windings of Power Transformers Based Upon Online FRA Using Capacitive and Inductive Couplings // IEEE Transactions on Power Delivery, Volume 26 , Issue 4 , Oct. 2011.
49. T. Schuette, E. Santos, Understanding the Breakdown Mechanism of Bushings and Implementing Appropriate Life-Cycle Oriented Maintenance Strategies // Western Power and ABB.
50. S. Arumugam1, S. Gorchakov, T. Schoenemann, Partial Discharge Investigations on a High Voltage Generator Cable Insulation through TF Method // 2013 Annual Report Conference on Electrical Insulation and Dielectric Phenomena, 20−23 Oct. 2013, Shenzhen, China.
51. J. Saraci The effects of high vibration on the steam turbogenerator machine of the unit B1 339 MW in thermal power plant “Kosovo B” // 2007.
52. I. Šperlín and J. Gurecký, “Advanced functions of network support based on ENTSO-E NC RFG in the czech technical standards,” 2016 17th International Scientific Conference on Electric Power Engineering (EPE), Prague, 2016.
53. U. Fuchs, S. Alwers Battery energy storage solutions // 3rd Internationa hybrid power system workshop, Spain, May 2018.
54. R. Oļekšijs and O. Linkevičs, “Possible solutions for ancillary service provision from combined heat and power plants in Latvia,” 2019 IEEE 60th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON).
55. M. Noroozian; N. A. Petersson; B. Thorvaldson and other Benefits of SVC and STATCOM for electric utility application // IEEE PES Transmission and Distribution Conference and Exposition, 2003.
56. F. O. Igbinovia; G. Fandi, Z. Müller and other Cost implication and reactive power generating potential of the synchronous condenser // 2nd International Conference on Intelligent Green Building and Smart Grid (IGBSG), 2016.
57. M. Nambiar, Z. Konstantinovic, Impact of using Synchronous Condenser for power system stability and improvement of short circuit power in mining projects // Mining Engineering , Vol. 67, Issue 1, pp. 38−44, Jan. 2015.
58. ENTSO-E Guidance document for national implementation for network codes on grid connection Cost Benefit Analyses // 2018.
59. T. Moger, S. Dodjoo, “A Comprehensive Analysis of Reactive Power Pricing a Competitive Electricity Markets” // Advances in Engineering, Science and Management (ICAESM), 2012.
60. GE Gas turbine upgrade selector – https://www.ge.com/power/services/gas-turbines/upgrades/catalog

61. Siemens modernization & upgrades for gas turbines – https://new.siemens.com/global/en/products/energy/services/performance-enhancement/modernization-upgrades/gas-turbines.html
62. A. Motamedi and M. Fotuhi-Firuzabad, “Ancillary Service Markets,” // 2007 Large Engineering Systems Conference on Power Engineering, Montreal, Que., 2007, pp. 316−320.
63. Y. G. Rebours, D. S. Kirschen, M. Trotignon and S. Rossignol, “A Survey of Frequency and Voltage Control Ancillary Services. Part II: Economic Features,” in IEEE Transactions on Power Systems, vol. 22, no. 1, pp. 358−366, Feb. 2007.
64. D. Siface and S. Canevese, “Optimal Sizing Tool for Batteries Providing Multiple Services to the System,” // 2019 AEIT International Annual Conference (AEIT), Florence, Italy, 2019, pp. 1−6.
65. R. Petrichenko, K. Baltputnis, D. Sobolevsky and A. Sauhats, “Estimating the Costs of Operating Reserve Provision by Poundage Hydroelectric Power Plants,” 2018 15th International Conference on the European Energy Market (EEM), Lodz, 2018, pp. 1−5.
66. R. Kumar and A. Kumar, “Reactive power cost characteristics for synchronous generator in deregulated electricity markets,” 2014 6th IEEE Power India International Conference (PIICON), Delhi, 2014, pp. 1−6.
67. I. Zicmane, K. Berzina, A. Sobolevskis and S. Kovalenko, “Assessment of Static Stability of Power System of the Baltic States in View of the Planned Synchronization with Networks of Western Europe to 2030,” // 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), Palermo, 2018, pp. 1−6.
68. Ulbig, A., Borsche, T., & Andersson, G. 2015. Analyzing Rotational Inertia, Grid Topology and their Role for Power System Stability. 9th IFAC Symposium on Control of Power and Energy Systems CPES 2015, New Dehli, India.
69. A. Chatzivasileiadi, E. Ampatzi, I. Knight, Characteristics of electrical energy storage technologies and their applications in buildings // Renewable and Sustainable Energy Reviews, vol. 25, 814−830, 2013.
70. J. Yu, J. Fang, Y. Tang Inertia emulation by flywheel energy storage system for improved frequency regulation // IEEE 4th Southern Power Electronics Conference (SPEC) , 2018
71. T. Mason, T. Curry, D. Wilson Capital costs for transmission and substations, 2012
72. A. Vafamehr, R. Moslemi and R. Sharma, “Aggregation of BTM Battery Storages to Provide Ancillary Services in Wholesale Electricity Markets,” // 2019 IEEE 7th International Conference on Smart Energy Grid Engineering (SEGE), Oshawa, ON, Canada, 2019, pp. 162−166.
73. V. Maask, A. Rosin and I. Roasto, “Development of Experimental Load Management System for Nearly Zero-Energy Building,” // 2018 IEEE 59th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), Riga, Latvia, 2018, pp. 1−5.
74. L. Petrichenko, L. Zemite, A. Sauhats, A. Klementavicius and K. Grickevics, “A Comparative Analysis of Supporting Policies for Solar PV systems in the Baltic

Countries,” // 2019 IEEE International Conference on Environment and Electrical Engineering and 2019 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), Genova, Italy, 2019, pp. 1−7.

75. R. Oļekšijs and O. Linkevičs, “Photovoltaic system application for combined heat and power plant self-consumption needs,” 2019 IEEE 60th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON).
76. E. Bompard, S. Zalzar, T. Huang, A. Purvins and M. Maser, Baltic Power Systems’ Integration into the EU Market Coupling under Different Desynchronization Schemes: A Comparative Market Analysis // ENERGIES p. 1945, no. 8 vol. 11, 2018.