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al. A. Mickiewicza 30, 30-059 Kraków
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Jessica Hastenteufel*, Max Dorow**,
Susanne Weber***

The impact of digitization on corporate controlling and the role of controllers

1. Introductory overview

In 1993, a university in Illinois published one of the first web browsers called "Mosaic". This browser contributed to the world wide web being adopted by a broad user base. As a result, ten million people were already using the internet in 1994 (Handelsblatt 2014, 2).

A lot has changed since then because digital technologies such as the internet are completely integrated into people's everyday lives. According to a recent study, around 67 million people in Germany used the internet in 2022 on a regular basis (Statista 2022, 4). Today, digitization encompasses many modern technologies, such as cloud computing, big data, artificial intelligence, the internet of things, and many others. It is therefore not surprising that these trends are being closely monitored by businesses to generate competitive advantages by using these technologies or at least to keep up with their competitors. The integration of new digital technologies is leading to fundamental changes in the corporate world. The associated effects on individuals and businesses are difficult to assess, diverse and subject to constant change due to an elevated level of innovation (Dorow et al. 2023, 5).

If we focus on the operational function of controlling, drastic changes can be observed in relation to digitization. In this context, technologies play a decisive role as they transform the environment in which controllers operate and in which their processes work. Thus, controllers will require a different skillset in the future

* IU International University of Applied Sciences (Germany), e-mail: jessica.hastenteufel@iu.org
** IU International University of Applied Sciences (Germany), e-mail: m.dorow@web.de
*** IU International University of Applied Sciences (Germany), e-mail: susanne.weber@iu.org

and their role within a company will change. Consequently, they must accept the adjustment of their tasks, business processes, and competences.

In this paper, the megatrend of digitization and the effects of selected technologies on controlling are examined. An overview of current controlling processes, the role of controllers and selected technology trends of digitization will be given. Finally, various parts of digitization and controlling are linked to present the current effects on the core processes of controlling and the role of controllers.

2. Corporate controlling and trends in digitization – an overview

2.1. Controlling processes

Controlling is one of the key operating functions in a business. Planning, management, and control are some of the core tasks of controlling. Since controlling – like the activities, processes, and tasks of companies – can be complex and diverse, it should be regarded as a process. To illustrate this process, the International Group of Controlling (IGC) developed a hierarchical structure of controlling (see Figure 1) in which they differentiate business processes, core processes, sub-processes, and activities (Schulze 2019, 33). For example, the business processes include controlling, whereas the core processes include underlying disciplines, such as capital expenditure controlling. The sub-processes and activities are subordinate to the core processes. The sub-processes include, amongst others, the implementation of the set-up (= a sub-process of capital expenditure controlling) and an associated activity could be, for example, the definition of the applied investment calculation methods.

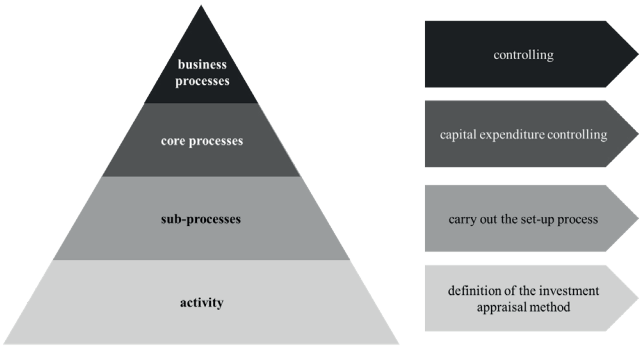

Figure 1. Hierarchical structure of the controlling process (International Group of Controlling 2017, 19)

Based on the IGC Process Model 2.0, controlling consists of ten core processes. At the sub-process level, these are described in detail by the objective, the content, the input, and output as well as by the process interfaces. The ten core processes can be differentiated into five essential and five additional core processes. The essential core processes of controlling that are analysed in this paper are (see Figure 2):

- the interrelated process of planning, budgeting, and forecasting,
- capital expenditure controlling,
- cost, performance, and profit accounting,
- management reporting,
- business partnering.

In addition, the IGC model includes strategic planning, project controlling, risk controlling and data management. These four core processes are usually conducted in cooperation with other organisational units. The last core process "further development" focuses on the organisation, the processes, and instruments as well as the systems and assures quality and is therefore differentiated from the other core processes (International Group of Controlling 2017, 18–20).

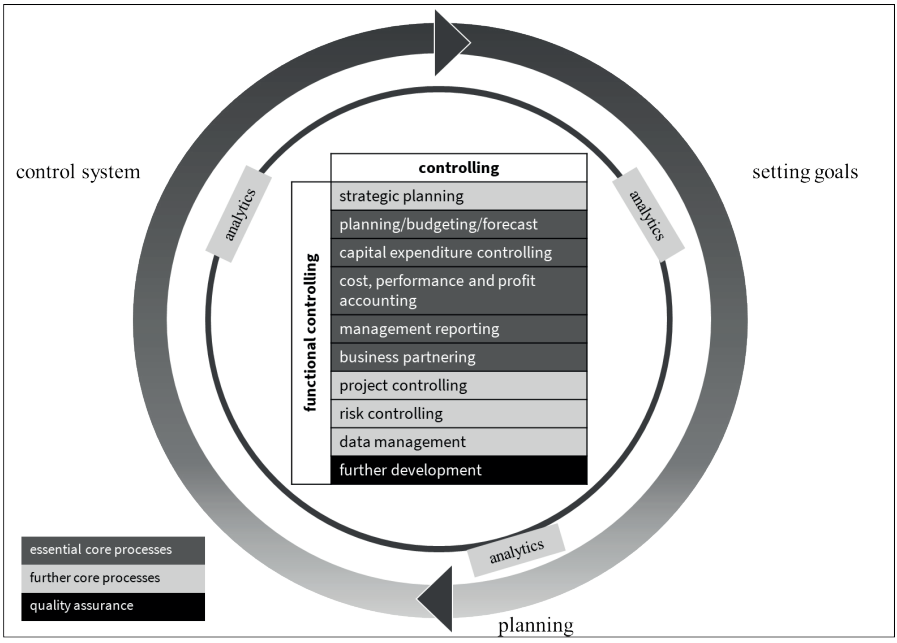

Figure 2. The IGC controlling process 2.0 (International Group of Controlling 2017, 20)

2.2. The traditional role and tasks of controllers

To examine the influence of digitization on the role and tasks of controllers, we must first look at the traditional role of controllers. The role and thus the tasks of controllers have evolved continuously over the years. Mäder, for example, divides the development of controlling into five stages:

- development stage (1500–1930),
- build-up stage (1930–1950),
- internationalisation and foundation stage (1950–1980),
- boom stage (1980–2010),
- consolidation and reflection stage (since 2010).

The last phase is characterized by the critical questioning of the current state of research in controlling (Mäder 2018, 103–107). According to this classification, controlling is currently in the consolidation and reflection phase, which analyses the current requirements due to changes in digital technologies and its effects on the role and tasks of controllers. In this context, the mission statement for controllers of the International Group of Controlling is important (see Figure 3).

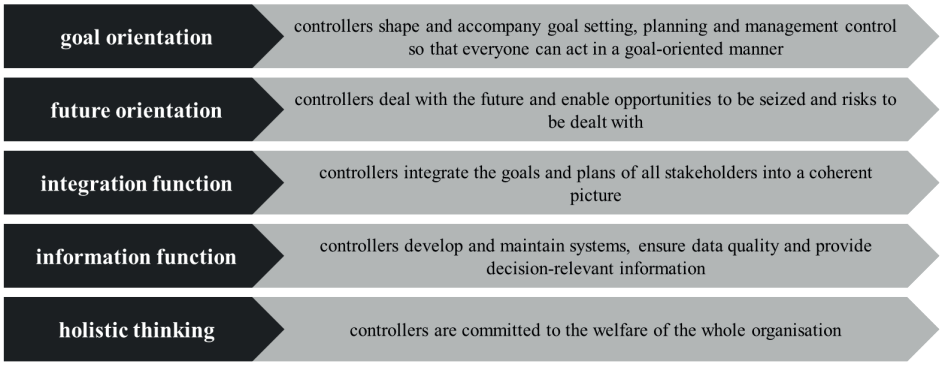

Figure 3. The controller's mission statement
(Internationaler Controller Verein, International Group of Controlling 2013)

Based on this model, it becomes clear that the tasks of controlling are diverse. If one now tries to link this mission statement and the previously identified core processes of controlling, the result is a hierarchical model in which the skills of a higher level are important for all subordinate levels. The controllers are therefore

so-called "knowledge workers" and must always fulfil all requirements that are related to this. These skills are then aggregated into cross-process controlling skills that are relevant for most of the core controlling processes. In contrast, the process-specific controlling skills are only critical for individual core processes (International Group of Controlling 2015, 39–42). Firstly, the skills from controlling activities are identified at the sub-process level and then aggregated at the core process level to be able to select the relevant cross-process skills (International Group of Controlling 2015, 43). Based on this, the skills can be divided into (Heyse, Erpenbeck 2011, XIII):

- personal skills,
- activity and implementation skills,
- social-communicative skills,
- technical and media skills.

Figure 4 shows the aggregated controlling skills based on the previously identified main processes. These are the traditional skills controllers needed in the past.

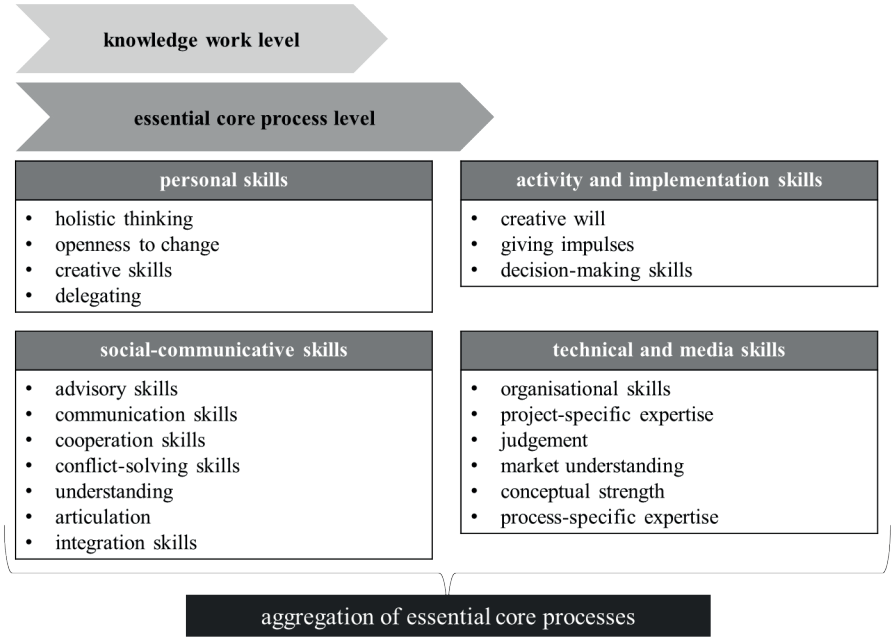

Figure 4. Traditional controlling skills map
(International Group of Controlling 2015, 38–101)

Now that the core processes of controlling and the essential skills of controllers were discussed, selected digitization trends will be presented before digitization and controlling are linked to analyse the influence digital technologies have on controlling and on the role and tasks of controllers.

2.3. Internet of things, big data and co. — key components of digitization

2.3.1. Introductory overview

Digitization includes the digital transformation and representation or implementation of information and communication or the digital modification of instruments, devices, and vehicles as well as the digital revolution (Bendel 2021b). Whereas IT was used in the 20th century primarily to automate, optimise, and modernise private households and workplaces, to create computer networks and to introduce software products (e.g., MS Office and ERP systems), since the beginning of the 21st century the focus has been on disruptive technologies and innovative business models as well as autonomation, flexibilization, and individualisation (Bendel 2021b). The technologies used and continuously developed in this context are diverse. In the context of controlling, mostly the following technologies are important as they generate or process data that is important for the previously identified core processes of controlling (Dorow et al. 2023, 10):

- internet of things,
- big data,
- cloud computing,
- artificial intelligence.

2.3.2. Internet of things

To put it simply, the internet of things is the networking of objects with the internet so that these objects can communicate independently via the internet and thus perform various tasks. The scope of application ranges from general information supply and automatic ordering to warning and emergency functions (Lackes, Siepermann 2018). It is a dynamic network that consists of identifiable physical and virtual objects that include technological properties to communicate, perceive or interact internally or externally (Borgmeier et al. 2021, 13). The internet of things uses a model which, according to Kaufmann and Servatius, consists of eight distinct levels, which are presented below (see Table 1).

Table 1

IoT reference model (Kaufmann, Servatius 2020, 6)

Level	Explanation	Technologies
1. perception	objects and data acquisition	sensors, actuators
2. connectivity	connectivity of devices and communication	network technologies
3. edge	local data storage and processing	edge computing
4. data storage	storage of large amounts of data	computing
5. data abstraction	data processing, stream aggregation, aggregation and pre-processing	big data, artificial intelligence, cloud
6. application	mobile and stationary applications, evaluations and reporting, control applications	app technologies
7. collaboration & processes	human interaction and integration of IoT data into business processes	API technologies
8. business model	building blocks of an IoT business model	IoT plattforms

Regarding controlling, it is important to understand why companies are integrating these complex and dynamic systems and what the main advantages and disadvantages are. Therefore, the general main advantages and disadvantages of the internet of things are summarized in Table 2.

Table 2

Advantages and disadvantages of the internet of things (Mattern, Flörkemeier 2010, 109; Kaufmann, Servatius 2020, 76 and 151; Ziegler 2020, 97; Soldatos 2021, 17 and 140)

Main advantages	Main disadvantages
increasing customer centricity linking data-driven services with production, making it possible to offer digital services in addition to the actual product	**data protection-oriented measures** esp. device security, network and communication security, database security, application protection
increased addressability of objects as each object can be influenced via electrical signals, productivity and work safety increase, while operating costs can be controlled better	**demand development** if demand does not increase at the same rate as efficiency, productivity and the degree of automation, there is a risk of a mismatch between supply and demand, which in turn can lead to a reduction in the required human labour

Table 2 cont.

Main advantages	Main disadvantages
basic sensor technology different types of sensors can digitally map the real world and machines can communicate directly with each other via databases or sensors, which can lead to time savings, faster reaction speed and increased data storage	**changes lead to additional work for the management of the company** numerous changes in a company require, for example, a reorientation of employees, a secure handling of complex IoT solutions and innovative business models, as well as different and sometimes more intensive control mechanisms
generation of so-called digital twins through logics and networking virtual images of real systems, high individuality and generation of knowledge through the creation of (new) data sources	

2.3.3. Big data

One of the core tasks of controlling is to collect, process and interpret data and to make it available to the decision-makers of a business. This is no longer simple data, but often big data. Big data refers to large, partly unstructured data volumes from different data sources (Iafrate 2014, 26), which are stored, processed, and evaluated by special data science solutions (Bendel 2021a).

There are various definitions for big data in the literature. What most definitions have in common, however, is that they focus on a different number of characteristics ("Vs") and a five-dimensional construct ("5Vs") (see Figure 5).

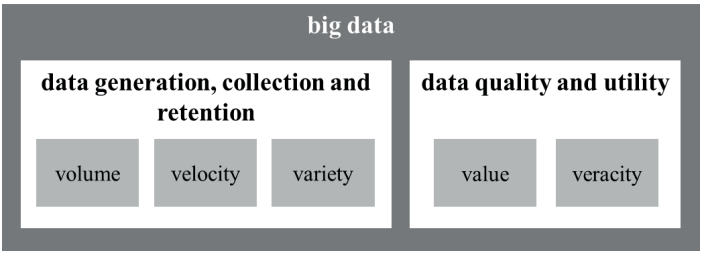

Figure 5. 5V of big data (Luengo et al. 2020, 1–2; Hastenteufel et al. 2021, 6)

Volume describes the huge amount of data. This data is generated at an extremely high speed (velocity) and should be processed in real time if possible. It comes in different forms (variety) and can be either structured, semi-structured

or unstructured, which is why data must first be cleansed to ensure its accuracy and credibility (veracity). In addition, data must provide added value (value) for a business. While the first three dimensions (volume/velocity/variety) refer to the acquisition, collection and storage of data, value and veracity focus on the quality and usefulness of data (Luengo et al. 2020, 1; Hastenteufel et al. 2021, 6).

Even though the collection of data is not new, it is the amount of data that is often overwhelming. This results primarily from the fact that

- countless devices and applications, such as sensors or social media, are continuously collecting information,
- storage capacities and technologies have increased enormously in recent years and at the same time the associated costs have dropped,
- the approaches and procedures in the areas of data science, artificial intelligence and machine learning have improved so much in the recent past that the knowledge gained from the data has also increased enormously (Hastenteufel et al. 2021, 7).

In addition, the increasing networking of already existing data opens new possibilities for companies to use data (Bloching et al. 2012, 73; Bendel 2021a; Hastenteufel et al. 2021, 7). However, for businesses to be able to use this data in a targeted manner, suitable procedures and tools are necessary. This is because the benefit of big data is usually not the amount of data or the data itself, but the possibility of recognizing previously unrecognized patterns and gaining insights by using data science and artificial intelligence (Luengo et al. 2020, 3; Hastenteufel et al. 2021, 7).

2.3.4. Cloud computing

Cloud computing comprises various technologies and business models for making IT resources available and charging for their use according to flexible payment models (Fehling, Leymann 2018). Here, IT resources (e.g., servers or applications) are not operated in a company's own data centre but are available on demand via the internet as a service-based business model. This leads to an industrialisation of IT resources and companies can reduce their long-term investments in IT by implementing cloud computing, as cloud solutions are usually much more cost-effective than classic IT solutions (Fehling, Leymann 2018).

Cloud computing is thus a model that allows a business to access a pool of configurable computing resources (e.g., networks, servers, storage systems) on demand, anytime and anywhere, conveniently via a network, whereby these can be made available quickly and with a minimum of effort (Mell, Grance 2011, 2).

The essential characteristics, organisational forms and levels of cloud computing are shown schematically in Figure 6.

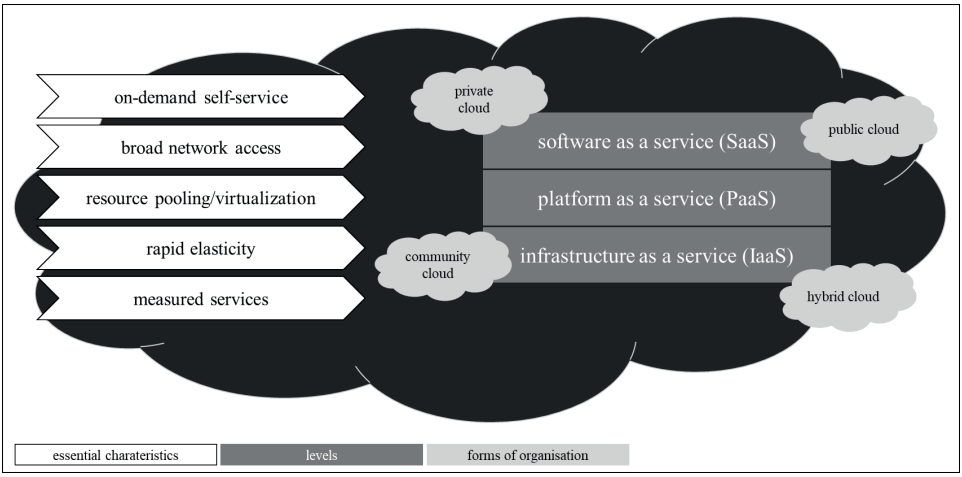

Figure 6. Principles of cloud computing (Hentschel, Leyh 2016, 569)

Cloud computing is characterized, among other things, by on-demand self-service, which means that server capacities can be rented and used by the user without human interaction. The access of a broad mass of devices via the internet is secured by broad network access. Since, depending on the requirements of the users, there is a need to scale these provided resources, resource pooling (concentrated form of virtual and physical resources with which they can serve several consumers) and rapid elasticity (scalability of resources) are important. Measured services serve to increase transparency for service providers and recipients by monitoring and automating the optimization of the use and availability of cloud computing services (Mell, Grance 2011, 2).

According to their organisational form, cloud solutions can be either private, public, community or hybrid. In a public cloud, services can be offered to the public and these services can be booked by several users, whereas access to a private cloud is only granted to a limited group of users (Bundesamt für Sicherheit in der Informationstechnik 2022). Based on this, a community cloud can be understood as an extension of a private cloud, in which not a single company but, for example, a group of connected companies wants to implement a private cloud, whereby not a single company but an entire group gains access to it (Mell, Grance 2011, 3). However, since the requirements for a cloud cannot always be categorised into the three cloud solutions described, hybrid solutions are often state of the art, which optimise the advantages and disadvantages of different cloud types (Zawaideh et al. 2022, 794).

Furthermore, cloud computing has various levels. IaaS represents the lowest layer of the model and comprises the provision of the basic physical IT

infrastructure (Hentschel, Leyh 2018, 9), whereby fundamental digital resources are available to the users, but the applications or operating systems can be managed and used independently (Mell, Grance 2011, 3). PaaS extends IaaS by providing additional content (Hentschel, Leyh 2016, 570–571). This can be, for example, complete development and deployment environments, operating systems required for this, any business intelligence services or database management systems (Microsoft 2022). SaaS extends PaaS and thus has the highest level of abstraction (Hentschel, Leyh 2018, 11). The goal is to provide the user with a required software as a cloud-based application, whereby the user is not given any configuration options about the underlying services such as operating systems, server structures, or network components (Mell, Grance 2011, 2).

2.3.5. Artificial intelligence

Among the numerous definitions available, artificial intelligence encompasses all procedures that are used to imitate or reproduce human thought processes with the help of a computer (Buxmann, Schmidt 2021, 6–7). Currently, the research field of AI is characterized by the attempt to replicate on machines the processes of human experience which determine human decisions and actions (Zhou 2021, 2). This is also referred to as machine learning, i.e., the learning of machines based on empirical values by means of algorithms. The concept of robotic process automation (RPA), which is based on this, goes one step further and carries out the learned activities in an automated and high-volume manner within software, so that a versatile process automation is achieved (Lawton 2021). Today, there are already different forms and possibilities of how AI can be used in companies in general and in controlling in particular.

3. The effects of digitization on the core processes of corporate controlling and the role and tasks of controllers

3.1. Impact on selected controlling processes

3.1.1. Planning, budgeting, and forecast

With the internet of things, data from intelligent objects are made available, which can contribute to an increase in flexibility and planning reliability within the planning process due to their granularity. On the one hand, this leads to real-time evaluation in forecasting. On the other hand, a clear demarcation between operational and analytical data management will no longer be relevant for the future, as both data sources can increasingly be considered simultaneously

(Gleich et al. 2017, 117). The large volumes of data are analysed and incorporated by using data science. If a business pushes this integration and includes externally generated data, this can be used within the planning process to uncover, for example, previously hidden market trends and relationships within existing data sets (Georgopoulos, Georg 2021, 55).

In-memory technologies ensure that the increased computing capacity of big data is processed within the planning process. Accordingly, the data relevant to planning is becoming more flexible via increasing computing capacities of cloud computing and more efficient main memory processing (Schmitz 2019). These newly created, structured, granulated data sets can then be integrated into the planning activities of a controlling department by filtering, e.g., through machine learning algorithms, and thus lead to relevant information within a brief time (Portal 2020, 70–72). In this context, cloud solutions that map the entire planning process of controlling and integrate various subsystems, e.g., sub-technologies, are a favourable and flexible way to optimise this core process (Wagner, Wernitz 2022, 17).

The main advantages resulting from integrative planning can also be identified in a comprehensive perspective, which enables the management to recognise deviations from the original plan within the various planning aspects considered and to react accordingly in a dynamic and risk-adjusted manner (FondsKonzept 2022). Different options for action can be calculated by risk-adjusted planning and a driver-based planning model in a volatile corporate environment. Examples are the so-called frontloading approach or the Monte Carlo simulation. Concepts such as the Monte Carlo simulation have been known for a long time, but they can only be used in the practical corporate environment due to the increasing availability of powerful IT infrastructures, since e.g., the calculation times are becoming increasingly shorter due to cloud computing or in-memory technology (Grund et al. 2020, 17).

Standardisation of the processes and the associated adaptation of technologies to the planning processes also mean that increasing automation and digitization in daily work release large capacities that can be used elsewhere (Schrader et al. 2022, 22). Likewise, medium-sized companies could increasingly access these technologies due to the increasing scalability of cloud technology. If, in the case of full integration, sovereignty over the planning logic is then transferred to the system, the company can positively influence both the planning output, the planning quality and the increasing dovetailing of the results of the strategic and operational planning elements (Horváth et al. 2019, 480; Langmann 2019, 23–25). For example, at this point it would be conceivable to have automatic evaluations of strategies according to a certain environment or business information from practice and, in conjunction with this, a digital recording, evaluation, and recommendation of controlling. In the case of automated forwarding, this would lead to operational

and strategic planning forming a control loop and the boundaries continuing to merge, so that information from both levels can lead to plan adjustments at the other level (Abée et al. 2020, 19–30).

However, planning is not considered by itself, as budgeting is created based on the determined information. Therefore, the operational individual plans must be integrated into a coordinated overall plan, which subsequently influences or is influenced by the strategic orientation of a company. The entire coordination and consolidation process, including the subsequent budgeting, thus benefits from a flexibilization of data and an increase in the exchange of information (Güler 2021, 116).

Advanced analytical methods are also relevant for planning, budgeting, and forecasting, as they use historical data to predict future events by using algorithms (Mayr 2022, 116). While one thinks primarily of forecasting here, the technological instruments also have positive effects on budgeting. For example, predictive analytics in budgeting can primarily contribute to deriving realistic, comprehensible objectives from the planning data and thus lead to a more positive and motivated attitude among employees (Koch et al. 2020, 56–59). Digitization thus necessarily increases the flexibility in this area of controlling, whereby rigid observation periods, e.g., of one year, could lose importance and an adjustment during the year is simplified (Hastenteufel et al. 2022, 4). If this core idea is expanded with visual support, such as an embedded real-time dashboard, the decision-makers of a business can consult an actual comparison at any time and from any location via the flexible ad-hoc budgeting of controlling (Horváth et al. 2019, 491).

When it comes to forecasting, evaluations of past periods are becoming increasingly less important, especially in highly volatile corporate environments, which means that proactive forecasting is becoming more important (Kieninger et al. 2017, 5). This highlights structure-discovering analytics, such as predictive or prescriptive analytics (QUNIS 2022). By using artificial intelligence, it is possible, for example, to apply complex mathematical analysis methods to increase the validity of forecasts (Horváth et al. 2019, 480). In this respect, cloud-based solutions not only ensure data processing and the creation of forecasts, but also make data available, provide cross-location benchmarks or, for example, allow information from accounting to flow into the calculations in a high-performance manner, which is not possible or only possible to a limited extent with conventional ERP systems (Heinzelmann 2022, 175). If the examples mentioned are carried out interactively, fully automated real-time simulations, driver-based forecast models and adaptable scenario models can be implemented. These are characterized by a creation that can be carried out more frequently, faster, more comprehensively and based on previously unconsidered data sources (also non-monetary data). By reducing interfaces, these integrative systems act automatically based on the underlying algorithms and initiate independent countermeasures (Grönke et al. 2017, 37–38). Thus, forecasts can also be created ad-hoc.

Looking at the influencing factors listed, it can be stated that they are dedicated to the overarching goal of achieving a more agile form of organisation. Table 3 structures and summarises these points.

Table 3

Current effects of digitization on planning, budgeting, and forecasting (Dorow et al. 2023, 17)

Effects on planning, budgeting and forecast through	
the internet of things	
– increase in direct data generation through the value-added process – increase in planning reliability through an increase in the population	– real-time data generation and the possibility of feedback to the systems – reactions to changes in the shortest time possible
big data	
– integrating large amounts of data, including external data, within the entire core process – increasing the heterogeneous exchange of information within planning, budgeting and forecast	– increasing efficiency, especially in the coordination and consolidation process of data – advanced analytics support budgeting and forecast by referring to the future
cloud computing	
– flexible planning intervals/adaptation to planning workloads – possibility to integrate sub-technologies within the core process – flexible implementation of complex forecast simulations (also for SMEs) – integration of further technologies to increase transparency	– minimizing the technology interfaces of planning, budgeting and forecast for the end users – agile cross-company planning is enabled
artificial intelligence	
– discovery of hidden market trends and relationships for integration in planning – evaluating complex planning models in a short period of time – discovering hidden market trends and relationships for integration in planning – evaluating complex planning models in a short period of time – implementing new planning models, such as the frontloading approach	– releasing previously tied-up capacities through the automation of standardized processes – increasing planning output and planning quality – increasing linkage of strategic and operational data – automated initiation of countermeasures in the event of deviations from the plan – enabling a control loop of integrative planning

3.1.2. Capital expenditure controlling

The core process of capital expenditure controlling consists of various input-based sub-processes that result in investment plans, investment reports or recalculations (International Group of Controlling 2017, 40).

In general, capital expenditure controlling consists of the assessment, selection, and control of significant investments (Rieg 2022, 899). It starts with the investment idea since capital expenditure controlling is influenced by implemented digital technologies. The investment requirement arises mathematically from the planning results already described, which can be circumscribed by a mathematical-analytical activity (Behringer 2021, 98). In the case of agile planning, there is already an intensified exchange of information here, which must be considered within the investment calculation. Especially cloud-based software such as SAP S/4 HANA can already facilitate communication and data access for investment controllers (SAP 2022). The improvement of communication leads to the emergence of discussions within various parts of a business, the discovery of bottlenecks by using IoT technologies and the identification of new investment needs, which can lead to a long-term improvement of the process start of capital expenditure controlling (Behringer 2021, 78).

After an initial exchange of information took place, investment controllers accompany the investment project by determining the investment amount, the profitability, and the underlying risks of a project (International Group of Controlling 2017, 40). This is the investment planning sub-process. Regardless of whether static or dynamic investment appraisal methods are used, the values must be analysed as precisely as possible and included in calculations to be able to carry out a targeted investment assessment. If the net present value method is used to calculate the discounted cash flows based on a fixed purchasing behaviour of customers over five years, a sharp rise in inflation, for example, can lead to this calculation no longer being applicable. Market data, pricing data, production data, research and development data, design data, tool data or process information and other data can be used as influencing factors in investment calculation (Mühlböck, Kronawettleitner 2022, 448). This example shows that capital expenditure controlling is strongly future-oriented and risky. It should be mentioned that not only a business itself bears this risk, but also the stakeholders (Wagner 2022, 239). Therefore, it is an essential task of capital expenditure controlling to deal with uncertain forecast data, for which small and agile control loops should be developed to be able to initiate any investment changes regarding the agile environment (Lamla 2017, 135). These control loops should in turn be used with big data. In practice, predictive analytics can help to forecast probable future values from historical data, which can then be included in the investment calculation (Schrader et al. 2022, 8). Integrated sensitivity analyses inform about the corresponding

risk (Langmann 2019, 11), which can reduce the uncertainty factor and increase the quality of the instructional content. If the diversity of data is combined with the learning mechanisms of artificial intelligence and the computational speed of cloud computing, coherent investment models can be developed that are already being used in practice, e.g., in asset management. They can automatically collect data from recent decades on financial investments, process them for investors or check and correct the decisions of investors themselves (EY 2023). The individual, clearly definable solutions in capital expenditure controlling are becoming comprehensive overall services due to multi-layered data (Horváth et al. 2019, 486).

If an investment has been planned using modern technologies, it is possible to combine this planning with other investment plans within a programme or to weigh up individual investments (International Group of Controlling 2017, 40). In practice, the number of courses of action poses a particular problem in this regard because, on the one hand, many alternatives lead to confusing content and, on the other hand, timing plays a key role. Investment options may arise, while others may expire and thus no longer be available (Schneider 2022, 38). Overall, controllers need to use digitization approaches to cope with ever-shrinking investment cycles (Abée et al. 2020, 20). If one wants to evaluate partial solutions, one can refer to the overall services above. However, to gain a comprehensive overview, the individual measures can also be evaluated coherently by using artificial intelligence and thus form a new integrative level of consideration. AI can then in turn complement this new layer of data so that new, up-to-date information is integrated into investment programmes (Foy 2021). It is also conceivable to integrate the growth business perspective, in which effects are operationalised that occur after the investment has been made (Kappes, Schentler 2017, 167). Standardized investment portfolios can be used to visualise the benefits of various programmes and present aggregated information on a dashboard via cloud computing (Vanini 2022, 284). The role of controllers is to monitor this process and incorporate their own experience into the selection of an optimized investment programme. An embedded reinforcement learning structure improves the future decisions of AI, which can successively increase the quality of statements about learning intervals (Foy 2021).

If the need for investment is confirmed through communication, if it is planned and an investment programme is decided, capital expenditure controlling must, among other things, observe investment decisions, create recommendations for action and recalculate investments.

The increased performance orientation described above must always be considered from a cost-benefit perspective, since businesses are subject to great uncertainties regarding the success potential of investments. Although it is possible

to scale evaluations, including cost-related ones, via cloud computing, excessive costs are associated with implementations or process changes in capital expenditure controlling (Güler 2021, 109). Partial integrations, such as the information networking of forecasts and capital expenditure controlling to take early countermeasures, will therefore predominate in practice (Müller 2021, 46). In contrast, far-reaching digital environment assessments must be subjected to an intensive individual cost-benefit analysis and are therefore likely to be found less frequently in SMEs than in large companies (Abée et al. 2020, 28). Finally, Table 4 summarises the influence of digitization technologies on capital expenditure controlling.

Table 4

Current effects of digitization on capital expenditure controlling (Dorow et al. 2023, 19)

Effects on capital expenditure controlling through	
the internet of things	
– bottlenecks and investment needs are uncovered – agile adjustment due to new data within fast control loops in capital expenditure controlling	– provides versatile industry data that helps in investment appraisal – provides the internal basis to carry out capital expenditure controlling on a real-time data basis
big data	
– provides influencing factors (multi-layered data) for inclusion in investment calculations – increases the quality of the content of the report	– reduces the risk of the organization and the stakeholders by enhancing metrics
cloud computing	
– increased information transparency in finding an investment idea – faster evaluation of related investment models – easier access to data by capital expenditure controllers	– more flexible information for relevant stakeholders of investments, e.g. by means of dashboards
artificial intelligence	
– learning mechanisms help to achieve accurate investment recommendations – versatile data use and complex algorithms are applicable in capital expenditure controlling	– sensitivity analyses become applicable and independently extended – new level of consideration: entire investment program decisions become comparable

3.1.3. Cost, performance, and profit accounting

Society is changing continuously due to digitization, which means that product life cycles are becoming shorter, and customers are demanding flexible products and services that are adapted as precisely as possible to their individual needs (Mayr 2022, 107–109). Businesses need to address these changing needs to maintain their position in the market. To guarantee a profitable operating process, controllers must evaluate this change within cost, performance, and profit accounting and collect relevant information.

Due to the permanently changing conditions in production, the number of employees in indirect areas such as marketing or IT is increasing (Mayr 2022, 104). Automation, high-tech and increasing digitization of business systems and processes lead to product-independent resources being increasingly tied up and costs rising as a result. At the same time, more intense competitive pressure can be observed due to digitization and the globalization of markets, resulting in increased cost pressure on companies (Günther 2018, 545). A central challenge for companies today is therefore to counter increasing cost pressure and changes in cost structure.

In this regard, in cost management a variety of instruments have been developed which can be applied in a solution-oriented manner depending on the area of application. These include, for example, flexible standard costing which serves resource-oriented cost planning as well as activity-based costing, with which transparency is created within increasingly complex business processes. In addition, product life cycle costing, in which the cost perspective is considered and managed over a product´s life cycle, is also used (Mayr 2022, 106).

All these instruments are based on data and are applied depending on the problem. Data quality can be identified as a particularly critical point. Therefore, the necessity to identify cost drivers along the value chain and to include them realistically in calculations is high. Cross-company information systems, such as a cloud-based integrative business intelligence system, are effective ways to meet these quality-assuring requirements (Georgopoulos, Georg 2021, 11). However, Monte Carlo simulation, for example, also benefits from increased data quality in cost and performance accounting. Data can be incorporated into business scenarios determined in real time and, through big data combined with external data, lead to better results (Grund et al. 2020, 17). These models can then be optimized by enhancing data with actual prices and observation of competitive prices, for example with machine learning, to create the highest possible transparency within this core process (Georgopoulos, Georg 2021, 48).

Looking at the approaches of digitization within cost accounting, we can see a higher agility, an innovation orientation, and a smarter use of data. An attempt is made to create a certain proactivity to successfully lead a business through constantly changing environmental conditions and to use diverse opportunities in this process (Becker et al. 2022, 1013). Initiative-taking cost management is

characterized by enforcing a consistent market orientation while considering the entire product life cycle. As rising fixed costs and overheads can be challenging for businesses, IaaS, PaaS, SaaS services can be implemented to modify or reduce fixed costs (Mell, Grance 2011, 2). Reactive cost reductions due to deficient performance indicators are thus a problem of the past and are replaced by an intra-year and ongoing cost analysis. This aims to secure sustainable competitive advantages and long-term corporate success. In contrast to hierarchical top-down planning, employees are actively involved in cost planning. Initiative-taking planning is thus characterized by communication and interdisciplinarity. Information systems that use the entire data of the digitally influenced cost, performance, and profit accounting create a centralised data model (Güler 2021, 130; Mayr 2022, 107–122).

It should be mentioned that the drivers of digitization can lead to structural changes along the entire core process of cost, performance, and profit accounting. This is especially true for material management, personnel policy, investment structures, process levels and product characteristics. The main effects of digitization on cost, performance and profit accounting are summarised in Table 5.

Table 5

Current effects of digitization on cost, performance, and profit accounting
(Dorow et al. 2023, 21)

Effects on cost, performance and profit accounting through	
the internet of things	
– increasing asset intensities and reduction of process costs – changing cost structure (rising costs)	– allows the inclusion of detailed data, e.g. machine data – allows individuality and feedback through controllable elements
big data	
– increasing cost pressure on companies through comparability – enables the inclusion of versatile data in cost, performance and profit accounting	– benchmark analyses in line with the market are enabled – a holistic approach is achieved
cloud computing	
– changing the cost structure (more flexible, dynamically adaptable) – central database of cost, performance and profit accounting can be accessed by many organizations and controlling departments – real-time data relationship for production adjustment	– enables individuality to be derived from holism – stand-alone solutions are consolidated into a unified system – employees and different valuation approaches can be better integrated into cost, performance and profit accounting

Table 5 cont.

Effects on cost, performance and profit accounting through	
artificial intelligence	
– new models of cost, performance and profit accounting, which, for example, consider the entire product life cycle – automated execution of computationally intensive processes – comprehensive scenario models for adapting offers	– evaluating of complex planning models in a short period of time – feedback and adjustment based on international data in real time – proactivity within cost, performance and profit accounting is developed

3.1.4. Management reporting

Standard reports, ad-hoc evaluations, or the creation of a dashboard are all based on data that is processed and prepared in management reporting. In the following, we will analyse the effects of digitization trends on the core process of management reporting, which includes data collection and preparation, report creation, plausibility checks, analysis, and commenting on and discussing the reports (Langmann 2019, 14).

If we consider data collection and processing, there are for example changes related to the internet of things. Current data from sensors within connected machines ensure that data is generated and available in real time, thus enabling real-time control of production processes (Georgopoulos, Georg 2021, 53). It should be mentioned, however, that the systems of agile organisations are communicating with their environment, which usually creates heterogeneous networks. The data provision of these networks must first be harmonized and based on sufficient data quality to enable a uniform and standardized analysis that is accepted within a business (Ploier, Mayr 2022, 156). Only in this way will data collected and provided by the controlling department remain the sole source of truth and thus the basis for all further reporting (Horváth et al. 2019, 488). AI-based bots enable these reporting process steps of data extraction, harmonisation, and plausibility checks from various sources to be carried out automatically (Langmann 2019, 17). It is also possible to identify relevant value drivers within data structure (Güler 2021, 125). Machine learning algorithms thus accelerate the approaches in management reporting and lead to quality improvements from the very first process step, providing more detailed and flexible access to information in terms of content (Müller 2021, 32–34). This also impacts the capacities in controlling, so that controllers must make fewer manual adjustments, data inconsistencies are avoided, and free capacities can be used for other tasks (Schrader et al. 2022, 10). To disclose cause-and-effect relationships and create sufficient transparency, it is important to pay attention

to the integration of interfaces when selecting the software used so that isolated solutions are avoided (Eymers et al. 2018, 124).

Big data technologies have a major impact on management reporting, as they can be used in a number of sub-processes. For example, the cause-effect relationships can be evaluated by using a statistically quantitative database (e.g., via sentiment analysis) (Langmann 2019, 15). Data science can significantly increase the plausibility of a report's content in terms of topicality and informative value by integrating external data, e.g., from social media or from the news, into management reporting. This also leads to a broader view of value drivers within value driver analysis, so that a detailed view on data is provided. This is also referred to as a drill-down (Georgopoulos, Georg 2021, 53–54).

However, data science not only allows for historical analysis. Rather, by advanced analytics, highly granular data can be analysed in real time, while external data can be related to facts within a business to complement management reports. Thus, a shift from past-related descriptive reporting to future-oriented data interpretation and enriched prediction of the impact on an organisation can be observed (Mödritscher, Wall 2022, 46). The indicated mergers of operational and strategic data levels can therefore be found in this core process. For example, the technologies described support so-called real-time reporting, in which standardized reports and dashboards are created automatically and in a customized manner for the management. Moreover, the agility of a business is guaranteed, and a competitive advantage can be generated (Langmann 2019, 17). Conceivable here are, for example, fully automated document postings, report compilations and automated corporate communication with tax auditors or tax consulting firms (Ploier, Mayr 2022, 153). Since management reporting includes individual elements of related core processes and encompasses already established reporting, there is also the possibility that new reporting formats will emerge (Huber 2017, 68).

Therefore, the role and tasks of controllers in this context must be reconsidered. In literature, reference is made to so-called self-service reporting, in which a management uses controlling systems, e.g., via apps, without contacting the controlling department (Georgopoulos, Georg 2021, 53–54). Reports based on voice control, reports on mobile devices or, for example, production information based on the current conditions in a factory open up new possibilities for management reporting and benefit from an increasing performance of consolidated IT systems (Langmann 2019, 16). However, it is questionable whether self-service reporting, by bridging the controlling function as a supplier of figures within the management reporting process, makes the entire tasks of controllers obsolete. Without the specialised knowledge of controllers and sufficient training and experience, there is always a risk of misinterpreting data (Wolf, Heidlmayer 2022, 18). It should therefore be noted that capacities that are released due to digitization should not disappear but should be used to focus on other controlling activities.

Overall, we can state that management reporting in general and financial, market or functional reporting specifically are affected by the selected digitization trends. While financial reporting tends to benefit more from increasing automation and the connectivity of the IoT, market and functional reporting will change in measures and overall concepts. Digitization is changing the past-related reporting requested by management into a future-oriented integrative instrument that adapts the innovations of the core processes of controlling. In contrast to traditional push reporting, in which controlling sends out the reports, we can observe that managers navigate independently through the reports and can thus analyse this consolidated information in a value-driver-oriented manner by means of drill-down procedures (Gräf et al. 2017, 61). In this more efficient world of pull reporting, the tasks of controllers will change. Table 6 summarises the effects of digitization on management reporting.

Table 6

Current effects of digitization on management reporting (Dorow et al. 2023, 24)

Effects on management reporting through	
the internet of things	
– real-time reporting is made possible through CPS – heterogeneous networks become evaluable for reporting purposes	– detailed data of value-added process can be linked in reports – increase in transparency through an expansion of the amount of data within reports
big data	
– allow for sentiment analysis as a quantitative data basis – extensive drill-downs are possible	– reports are improved by highly granular data in real time – future orientation and traceability within reports is increased
cloud computing	
– cause-effect relationships are disclosed by avoiding isolated solutions – increases transparency within reports through individual presentation	– self-service reports can be accessed by managers – reports are created based on consolidated IT systems
artificial intelligence	
– single point of truth is ensured by AI systems – data extraction, harmonization and plausibility checks can be automated within the process – releases capacities for controllers	– relevant value drivers can be identified and a more detailed and flexible access to content is provided – automated reporting can be adapted in an agile manner

3.1.5. Business partnering

In contrast to the essential core processes explained above, the elements of business partnering are not limited. Rather, the sub-processes are designed individually and according to individual needs (International Group of Controlling 2017, 50). The core process of business partnering, and the sub-processes cannot be clearly defined, so that an extensive mapping of different company-specific competences is necessary (Meier 2022). In the following analysis, two selected sub-processes of business partnering are selected as examples, which are particularly relevant. On the one hand, decision-making is considered since management must always make decisions and the decision-support function of controlling can influence the organisation of a company significantly. On the other hand, the promotion and transfer of special knowledge in a business are dealt with, as this aspect serves to secure the future. Both forms of business partnering in focus are therefore highly relevant to the effects of digitization trends on core processes described so far and have a considerable influence on a company´s success. To include big data in decision-making, for example, analytical procedures such as aspirational, experienced, or transformed processes can be used. In this context, aspirational includes the confirmation of decisions already made and the explanation of wrong decisions. In contrast, experienced methods evaluate different decision alternatives by using data science. In transformed decision-making, cause-and-effect relationships are revealed based on decision alternatives and dependencies of different data (e.g., market data). Moreover, decision alternatives are modified to find the best solution (Mödritscher, Wall 2022, 45). If controlling deals with these technologies and uses new instruments in adjacent core processes, a more extensive knowledge leads to the fact that a stronger decision-making participation can be observed, in which, however, the managers should always be included in decision-making and evaluation (Schneider 2022, 86–87). Extensive automation technologies, highly volatile business environments and increasing competitive pressure serve as drivers in this regard, so that controlling is increasingly involved as a sparring partner of the management within the decision-making processes (Wolf, Heidlmayer 2022, 6–15). AI systems can be used, for example, to check decisions based on big data by means of so-called A/B tests, to uncover correlations using data mining and thus to create hypotheses for decisions, or to generate new models via machine learning and complex algorithms in order to be able to interpret alternatives more easily, which ultimately leads to a qualitatively better decision (Wolf, Heidlmayer 2022, 20–27). Optimized starting points of a data landscape as well as data preparation thus lead to the active decision-making process becoming more efficient, while ensuring a high effectiveness of the measures (Kieninger et al. 2017, 6–7). Data science enables the management to make decisions faster, proactively and on a specified information basis. Ensuring

data quality is also relevant, as the large quantity and variety of data may lead to incorrect decisions (Müller 2021, 14–84). Information based on big data can also be used in the guidance process. For example, the actions of individuals are based on information they easily remember. New forms of visualization, such as treemaps or Sankey diagrams, contribute to simplifying this guidance process and can be displayed or communicated to the management via a cloud computing-based system (Mödritscher, Wall 2022, 53). However, it is also conceivable to integrate the data obtained into traditional instruments, such as a balanced scorecard, and thus enable managers to routinely deal with new information. In any case, information systems based on cloud computing ensure that decision-making has a clear basis and that various levels of reporting can be flexibly addressed to make the best decision possible (Linsner 2017, 73–74). An openness of the management to new forms of technology is essential in this context.

To be able to make the best possible decisions, companies highly rely on expert knowledge and on modern technologies. This makes knowledge transfer within an organisation indispensable. Controlling can take an expert position in this process since the existing system landscapes can be transferred to the knowledge process. For example, there are platform solutions based on cloud computing that distribute specific knowledge within a company (Horváth et al. 2019, 474). Moreover, they can be used to

- facilitate collaboration with experts via interfaces,
- enforce data governance,
- ultimately integrate AI.

This includes the possibility of including cyber-physical systems (CPS) and thus accessing the data of the IoT within a knowledge database as well as retrieving the data of the knowledge database via CPS (Tridion 2022). There, the entries maintained can then be checked and corrected automatically, e.g., by using innovative, AI-based methods, to ensure they are up to date. In addition to the sustainable development of internal company knowledge, there is also the possibility of implementing external knowledge networks or renting knowledge services to expand a business' expertise (Elste, Binckebanck 2017, 923). Furthermore, the idea of a centre of knowledge is becoming more popular due to better networking. The tasks of reporting, the processes or even the technical specific knowledge are pooled in one department, so that the advantages of standardisation such as bundling effects, efficiency increases or completely new organisational units are the result (Eymers et al. 2018, 123). If new centres of expertise are created in businesses, they can in turn provide consulting services for other divisions, with controlling acting as a data-specialised consultant for example (Langmann 2019, 41). Finally, digital competences built up by controlling can be further concentrated by digitization trends in a business and thus lead to increased knowledge

(Abée et al. 2020, 45). Like other main processes, the best level of integration of digitization within knowledge transfer must always be determined individually.

Table 7 summarises the influences of digitization on the decision-making process and the promotion of business expertise through controlling.

Table 7

Current effects of digitization on business partnering (Dorow et al. 2023, 26)

Effects on management reporting through	
decision-making process	promoting expertise
the internet of things	
– allows for a larger data base for decisions to be evaluated – real-time reporting based on the IoT leads to ad-hoc decisions – increases data quality of decisions	– knowledge is made accessible and explained with the help of CPS data – data updates of the CPS are automated by means of a knowledge database
big data	
– decisions become more transparent and easier to analyze – new methods (aspirational, experienced or transformed) are included in the decision-making process – proactivity is enforced within decisions	– knowledge base is significantly expanded and verifiable – misinterpretations are avoided due to an increased data basis
cloud computing	
– can lead to a higher level of decision-making participation by the controlling department – present simple graphics to simplify decision-making – connect different reporting levels of an organization to simplify decision-making	– company-wide solutions such as portal solutions serve as a central source of information – enable the use of data governance or other IT connections – access to third-party knowledge services is enabled – new organizational units (e.g. data labs) and roles can be created – collaboration with experts is facilitated
artificial intelligence	
– decision alternatives can be calculated, and intelligent decision models are created – complexity promotes the need for controlling as a sparring partner – decision alternatives can be interpreted more easily – feedback of the effects of decisions on the decision alternative itself is possible	– new forms within the knowledge databases, such as an automated correction database, are enabled

3.2. Impact on the role and tasks of controllers

The results of the effects of digitization trends on the essential core processes of controlling show a clear expansion and shift in controlling activities. Thus, IT systems will increasingly take over and fulfil tasks that are traditionally primarily assigned to data collection, processing, and distribution in the respective areas of controlling. Furthermore, the degree to how controlling functions and which controlling competencies will become more relevant, is influenced by the degree of integration and the use of these IT systems. In addition to a shift in roles, the literature also discusses whether future scenarios exist in which controllers become redundant within a business that uses digital technologies (Losblicher, Ablinger 2018, 66). It is assumed here that there will not be a substitution of controllers, but rather an expansion of their role and a modification of their tasks. This is justified, among other things, by a higher digital demand, a stronger competitive situation, greater complexity in general, expanded areas of responsibility for controllers, and the need to balance the limits of automation and AI (Losblicher, Ablinger 2018, 55). This assumption is the basis for considering established role models, as otherwise controlling could be classified as obsolete. However, to develop a starting point that also relates to the influence of digitization trends on controlling, the following roles of controllers will be considered:

- service provider,
- business partner,
- functional leader,
- pathfinder.

If controllers are described as service providers, their focus is on creating reports and providing data (Langmann 2019, 42). This role is the basis for all other controlling roles and is linked to the role model of the traditional controller. Thus, the core tasks of the service provider are (Langmann 2019, 43; Seefried 2017, 60):

- standardized cost accounting,
- consolidation in the annual financial statement,
- planning,
- reporting,
- commenting,
- further calculations,
- the execution of other standardized processes.

This role is linked to the implementation of the digitization technologies described, so that the goal is to further consolidate the data provided by IT systems and to pass on relevant information to the management. However, if the scope of services of digitization trends within an organization is broadened, this

outdated form of controlling becomes obsolete, so that in a flexible and agile corporate environment only little or even no added value can be generated by service providers (Hastenteufel et al. 2022, 7).

In addition to traditionally oriented service providers, the role of business partners is already established in many businesses. In this role, controllers function as idea providers and drivers for the management and increasingly take on a role between traditional controlling and management. Proactivity, ensuring organisational control and the architecture of the control system are their main tasks (Seefried 2017, 60). Controllers act on an equal footing with managers, so that independence and self-initiative are highly relevant regarding the implementation and coordination of strategic and operational measures (Hastenteufel et al. 2022, 6). Through the continuous use of new digital technologies and the automation pursued with them, controllers are enabled to use released capacities for management consulting related tasks. The aim is to optimise the decision-making process and thus establish long-term financial success for a company (Langmann 2019, 42). Through authenticity and storytelling, business partners ensure that information is interpreted and used correctly by the management (Haufe 2020). Controllers are thus to be integrated as sparring partners for management (Schöning, Mendel 2021, 47).

If controllers act as functional leaders, their main tasks are to manage and establish business-wide guidelines and standards for handling data. For this purpose, controllers develop, publish and document these and monitor their implementation (Langmann 2019, 43). Digitization is driving the importance of this role, as the number of IT systems is increasing and with it the amount of data. However, there are also problems associated with advancing digitization that functional leaders are supposed to avoid. On the one hand, they are used to avoid the situation of information chaos in which inconsistent or contradictory data arise. On the other hand, incompatibilities between information systems, information overload and data uncertainty, especially of personal and competition-relevant data, are to be counteracted (Heimel, Müller 2019, 413–414). The increasing availability of data, the diversity of data landscapes and the higher sensitivity regarding data protection are thus the main drivers of this role. However, the increased volume of structured and unstructured data within big data in combination with cloud computing pose challenges for controllers (Langmann 2019, 44).

In contrast, pathfinders focus on future trends in digitization and various analytical topics and try to examine which selected methods can be meaningfully implemented within a business so that controlling systems and methods always remain up to date (Schäffer 2017, 29). They can also be identified as drivers of change processes within controlling, which links them to data scientists in terms of their proximity to analytical topics (Langmann 2019, 43). Data scientists, in turn, work operationally with data evaluations and structures. For example, they know

various database models, how to access them, transform data, programme queries, visualise them and link them to a task (Aunkofer 2022). It is conceivable that controllers, as pathfinders, transfer innovations of digitization to business models and hand them over to data scientists for an operational evaluation to implement the respective questions. To do this, controllers need extensive technological skills, the will to continuously expand their knowledge, to act with foresight and statistical knowledge (Hastenteufel et al. 2022, 9). This example illustrates the effects of digitization on controlling, whereby the pathfinder has the highest degree of digitization and presents itself as a connection between business controlling and data-driven technology (Langmann, 2019, 45).

If we look at the distinct roles of controllers, we see that they make sense depending on the degree of digitization in a business. However, the roles described should not be seen as static or fixed. For example, pathfinders can also take on tasks of functional leaders if this is necessary in the respective situation. It always depends on a company and its individual circumstances. It seems logical to continue to observe developments in practice and thus to uncover possible sub-roles or further development stages of their role. However, a multitude of other roles already exist today, but they do not always overlap. For example, there are scorekeepers, data scientists, data engineers and decision scientists, to name but a few (Schäffer, Brückner 2019, 21). Whether a controller takes on all these roles, specialises, or how exactly the roles exist in a business can only be answered individually.

If we now combine the role descriptions presented here with the previously considered traditional role of controllers, various skills can be highlighted. If we build on the role of the service provider, the required competencies of the business partner, the functional leader and the pathfinder can be derived from this. Since the development of the various roles in controlling is ongoing, the following ideas are based on a Delphi study conducted by WHU in 2019, in which 448 participants with controlling expertise from various hierarchical levels took part and which can therefore be regarded as a starting point (Schäffer, Brückner 2019, 20). The aim is to transfer these research results to the skills map presented in figure 4 and to link them. For this purpose, the Delphi study looks at the required skills of selected roles in controlling. These are then assigned to the originally developed skills map, which refers to the core processes of controlling (Schäffer, Brückner 2019, 27). More frequently occurring required skills of the study are then aggregated under the originally selected characteristics of the map, while skills that could not be assigned were added in italics. A colour coding indicates the intensity of the required competence level. Finally, Figure 7 shows which of the traditional skills are becoming more important and which new skills will be relevant in the controlling of the future.

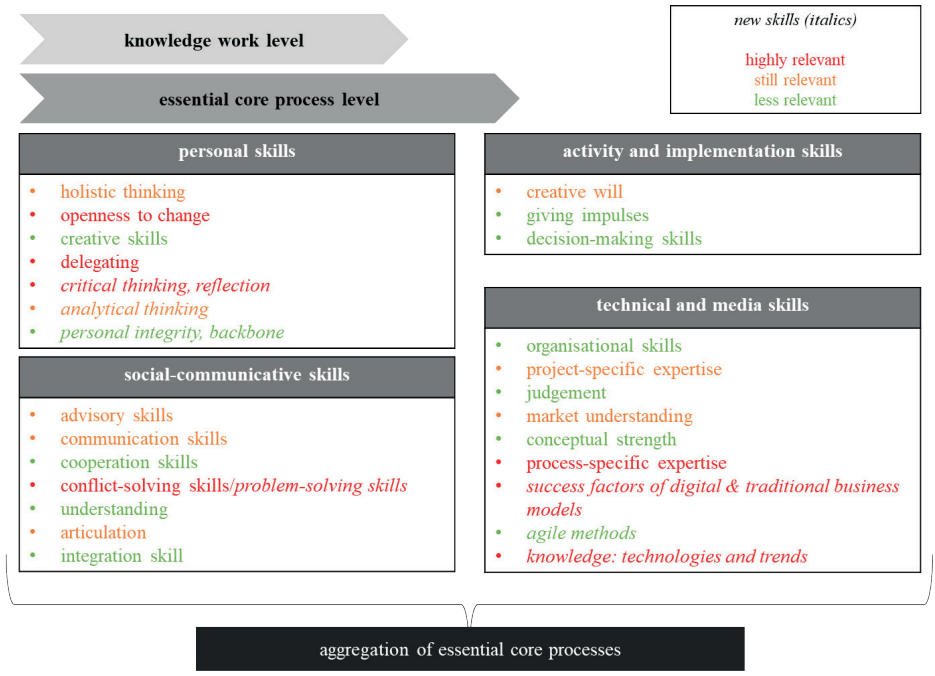

Figure 7. Modified controlling skills map
(International Group of Controlling 2015, 38–101, Schäffer, Brückner 2019, 27; Dorow et al. 2023, 30)

4. Concluding remarks

This paper investigated the extent to which the megatrend of digitization impacts the processes of controlling and how this is reflected in the role and tasks of controllers. In doing so, the competences required for controllers to master the processes were analysed. Based on this, a skills map was developed that refers to the traditionally required competences in controlling from 2015.

To value the technical orientation of this paper, selected key trends in digitization – the internet of things, big data, cloud computing and artificial intelligence – were examined. It was shown that these technologies differ from each other, are in various stages of development and therefore offer individual use cases for controlling departments or have different effects on them.

Subsequently, these technologies and controlling topics were linked and in this context the effects of digitization trends on controlling tasks were analysed. The

focus was on the core processes of planning, budgeting, and forecasting, capital expenditure controlling, cost, performance and profit accounting, management reporting and business partnering. It became clear that the individual controlling core processes are all affected by these technologies in diverse ways. In addition to general changes in the processes, risks, but also opportunities, can be identified through the targeted use of these technologies, depending on the design of the respective process. Numerous effects of selected technological trends on these controlling-specific core processes were described and analysed accordingly.

Based on this, the traditional skills map of controlling could be modified, new skills for emerging roles in controlling could be evaluated and related to the already elaborated information. It could be pointed out that some skills are increasingly important, while others become less relevant. In addition, new skills were also identified which modern controllers should focus on.

What do the technologically influenced future of controlling and the future role of controllers look like? This paper has shown that the environment of controllers is subject to constant change. Digitization affects the environment, people, and businesses. Therefore, new types of technologies also influence the described controlling processes in different intensities, characteristics, and diversity. This means that controlling experiences a change in tasks and responsibilities. Terms such as increased agility, proactivity and increasing automation have come up repeatedly in this paper and will continue to force controllers to develop new skills in the future.

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Summary

Digitization is a megatrend that strongly influences organisations and is reflected in all business processes and operational functions. It is therefore not surprising that controlling is also affected by digitization. This paper first defines and explains the key sub-processes of controlling and describes the traditional role and tasks of controllers that are derived from this. Next, selected technologies such as the internet of things, big data, cloud computing and artificial intelligence are described in detail and their influence on controlling and the role of the controller is analysed. It is shown that digitization is already having a significant impact on controlling and still holds considerable potential for the future. This will also lead inevitably to a continuous refinement of the role and tasks of controllers, whereby they will have to further expand their knowledge and skills in the future.

JEL codes: G39, M19, M49

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Aneta Kosztowniak*

The impact of markups and wages on changes in the level of inflation in Poland**

1. Introduction

In order to limit the negative impact of price increases on real economic processes, many central banks treat the fight against inflation as a key priority of their economic policy. Anti-inflation policy evolves from a Keynesian (demand) approach using fiscal policy tools, through a monetarist (supply) approach focused on regulating the amount of money, to comprehensive monetary policy instruments, including mainly interest rates, open market operations, reserve requirements or non-standard instruments of portfolio reduction bonds and others.

Isolating the most effective ways and tools to fight inflation is not easy, taking into account the unprecedented overlapping of numerous events such as the aforementioned COVID-19 pandemic and the energy crisis related to Russia's aggression in Ukraine. These events caused numerous disturbances in the monetary and fiscal spheres, business activity (in the areas of supply chains or investment policy in the domestic sector and foreign trade), as well as in the functioning of households (in the area of employment or income). They were the source of numerous shocks of an exogenous and endogenous nature, on which financial policy in the short and medium term often has a limited impact, resulting in the consolidation of inflation expectations in the economy.

This situation forces us to verify the existing theoretical and empirical studies on the determinants of the CPI and the channels of influence. Identifying whether we are dealing with demand or supply inflation, short- and long-term paths of inflation/disinflation in accordance with the model Philips curve. This situation

* SGH Warsaw School of Economics, Collegium of Management and Finance, Department of Applied Economics, e-mail: aneta.kosztowniak@sgh.waw.pl, https://orcid.org/0000-0001-6088-1899.
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also compels us to model inflation determinants not only focused on changes in the level of core inflation, fuels, energy, food, but more broadly, taking into account inflationary impulses from the enterprise sector and the labor market, e.g. in terms of markups and wages.

Literature information from recent years (after the outbreak of COVID-19) indicates that enterprises are trying to hedge against inflation, e.g. in the form of raising markups and employees in the form of wage increases to compensate for the decline in the purchasing power of nominal wages. The aforementioned increase in markups and wages, resulting from prudential motives, has an impact on the supply and demand side on price growth, making it difficult and extending the time needed to lower inflation.

The aim of the study is to analyze the impact of markups and wages of enterprises on changes in the level of inflation in Poland in the years 2007–2022.

The following research hypothesis was formulated: The increase in inflation expectations and future production costs in the economy stimulated the growth of enterprises' markups, limiting the effectiveness of measures to counteract inflation in Poland between 2007–2022.

Among the research methods available, the analysis of literature studies in the field of monetary policy and statistical analysis methods based on data published by the National Bank of Poland (NBP) and the Central Statistical Office (CSO) were used. The impact of markups and wages on changes in CPI were assessed using the VECM model, the impulse responses and variance decomposition.

2. Literature review

In the process of formulating monetary policy, including the assessment of inflation processes in the economy, central banks use numerous inflation measures, including core inflation indices, which, albeit with varying degrees of precision, allow us to approximate the unobservable trend of increasing the general price level. Core inflation is that part of inflation which is related to inflation expectations and demand pressure and which is not directly dependent on supply shocks. Its advantage is that it approximates the medium- and long-term trend in the growth of prices of consumer goods and services (Consumer Price Index, CPI) in the economy.

Core inflation shows the tendencies of their changes which are less subject to seasonal fluctuations and those resulting from supply shocks, which are most often of a temporary nature. In addition, it indicates the part of inflation which is more closely related to the monetary policy pursued than in the case of other parts and is useful in (ex-post) analyzes of the direction and scale of the impact of the pursued monetary policy on inflation and its measures, which are generally less volatile in than the CPI inflation rate (NBP 2023a, 2023b).

In the fight against inflation, a particularly difficult problem is the impact of price increases on the expectations of economic agents as to price dynamics in the future. This element is particularly important when there is a long-term price increase. It may turn out that as a result of the emergence and subsequent consolidation of inflation expectations, the wage dynamics will "overtake" the price dynamics, not only eliminating the possible positive impact of creeping inflation on changes in real economic categories, but even causing a regression. Counteracting the effect of inflation, while consolidating inflation expectations, was particularly difficult, e.g. in the 1970s and 1980s. As a result of the first and later second energy crisis (1974–1975, 1979–1980), the rate of economic growth slowed down and unemployment increased. At that time, it was difficult to overcome inflation by traditional methods of economic policy (Keynes 1947) and to analyze it scientifically (Friedman 1959, 1970, 1984; Modigliani 1977).

In the context of market disturbances caused by the COVID-19 pandemic and the period of war in Ukraine, it is important to lower high inflation expectations and diagnose the causes of changes in other price indices that determine the inflation felt by consumers. Since from the beginning of 2021, the core inflation and CPI indices in Poland (as well as in the world) showed a clear upward trend. Finally, in Q1 2023 in Poland, these indicators reached the following levels: CPI and core inflation excluding administrative prices will reach 17%, core inflation 15%, mean trimmed 16%, respectively, excluding most volatile prices 15% and food and energy prices 12%. The main components determining the level of CPI inflation were core inflation, prices of food and non-alcoholic beverages and energy prices (CSO 2023; NBP 2023b).

A strong inflation impulse caused by the increase in the cost of energy raw materials affects the increase in the prices of many goods and services, determining the increase in production costs, and in subsequent stages may cause a markup-wage spiral as well as a price-wage spiral (especially from Q2 2021). Thus, these impulses in Poland contribute to fueling inflationary processes, making it difficult to combat. Just like the current energy crisis, the previous energy crises were also a challenge for many monetary institutions, including those in the largest economies such as the USA, Great Britain, France, or Japan (Kosztowniak 2022, 183–210).

In addition to the aforementioned inflation expectations or energy crises, the following are listed among the main causes of inflation in the theoretical and empirical output:

- Demand gap and expansionary budgetary policy stabilizing the economic situation or stimulating (sustaining) an increase in expenditure in the economy (demand-pull inflation), resulting in an unbalanced state of public finances (Okun 1970).

- Supply shocks – in the form of changes in productivity, changes in oil resources, or changes in food resources, caused by weather changes or interruption of supply chains, as at the beginning of the COVID-19 pandemic; changing both the quantities of goods and their prices that are delivered to the market (Dudek 2008, 71–84).
- Demand shocks – reflecting changes in consumer behavior on the demand side as a result of changes in preferences or resulting from consumer decisions (Dudek 2008, 85–92).
- Existing market structures of producers on the market or in the branch producing goods and services (e.g. monopoly, oligopoly or other) – determining the possibility of shaping the price, supply, demand and, as a result, the size of the surplus of producers and consumers on the market (Perry 1982, 197–205; Foster et al. 2008, 394–425; Traina 2018; Dąbrowski 2016, 108–112; De Loecker, Unger 2020; Kosztowniak 2023).
- Import of inflation in the form of purchase of goods and services from abroad (the scale depends on the share of imports in GDP) (Wang et al. 2013).
- Development of the so-called wage-price-push in the conditions of increasing wage demands from employers by employees or competition for the distribution of newly created value, or an increase in wage-price spiral risks in the period after the COVID-19 pandemic (IMF 2022, 51–69; Boissay et al. 2022).

3. Empirical research review

One of the interesting studies explaining the increase in margins by enterprises at the turn of 2021–2022 in the American economy is the study conducted by Glover, Mustre-del-Rio and Ende-Becker (2023, 1–13). The activities of a monopolistic enterprise adjusting its activity and pricing policy to the increase in marginal costs and higher demand were analyzed. The authors pointed out that companies raise prices (markups) because:

- they expect higher costs to replace current inventory as it is sold,
- or in anticipation of higher marginal costs in the future, wanting to smooth out price increases over time, rather than raising them sharply and abruptly.

Generally, a profit-maximizing monopolist chooses a price that equates marginal revenue with marginal cost, and any change in price leads to a loss of profits. Changes in firms' running marginal costs or the demand for their products can contribute to inflation as firms adjust their prices to maximize profits. The total price change can always be understood as the combined effects of changes in the

marginal cost of production and changes in the firm's margin. Markups may or may not contribute to inflation:

- when the monopolist's marginal costs increase, markups decrease,
- but when the demand for the monopolist's products increases, the markups increase.

The more important findings include the statement that companies raise their markups in the present to mitigate price increases they expect in the future. This means that future costs may increase inflation in the present, through markups.

The empirical research by A. Glover, J. Mustre-del-Rio and A. Ende-Becker (2023, 11) on the American market shows that in 2021 the increase in markups probably contributed to the increase in inflation by over 50%, which was a much higher contribution than in the previous decade. However, they note that the margin itself is held back by a number of unobservable factors, including changes in demand, but also changes in firms' expectations of future marginal costs. The decline in markups in the first half of 2022 (even as inflation hit high levels again) was consistent with companies raising markups in 2021 in anticipation of future cost pressures. They also found that the increase in markups was similar across industries, with very different relative inflation rates in 2021, which was also consistent with the aggregative increase in expected future marginal costs. They also stressed that the increase in markups was likely a signal that price setters expect a steady increase in future production costs.

The risk of the expected wage-price spiral may vary in intensity in individual EU countries. From previous analyzes, Boissay et al. (2022) finds that the correlation between wage growth and inflation has decreased in recent decades, and that other institutional factors, such as a high degree of firm pricing power, declining bargaining power, and declining trade union membership, seem to limit the risk of a wage-price spiral developing.

As regards the growing wage pressure, important conclusions were also presented by the International Monetary Fund (IMF) in the World Economic Outlook report from 2022. It indicated that rising inflation, positive growth in nominal wages, falling real wages and falling unemployment characterized the macroeconomic situation in 2021 in many economies around the world. Although unusual, such conditions are not "unprecedented" because there have been 22 similar episodes in the group of developed economies analyzed over the past 40 years (and in several over the past 60 years).

According to the IMF, many economies have seen price inflation skyrocket since 2021 as adverse "supply shocks" hit the global economy and labor markets were tense in the wake of the severe COVID-19 shock. The Fund notes that the

rise in inflation has raised concerns among some observers that prices and wages may begin to feed each other and accelerate, leading to wage-price dynamics. However, empirical analyzes and models based on real firm costs of historical episodes similar to the current one suggest that they were not usually followed by a wage-price spiral. In fact, on average, inflation then gradually declined, with nominal wages gradually catching up over several quarters. However, in some cases inflation remained high for some time.

The Fund indicated that wage dynamics in 2020 and early 2021 were poorly explained by inflation expectations, and the stagnant labor market situation likely reflected an unusual constellation of shocks caused by the COVID-19 pandemic. Model-based analysis of wages and prices in 2020–2021 shows different underlying shocks, i.e. wages were effectively driven by capacity and labor supply shocks, while private saving was important for price developments. In the second half of 2021, wage growth was relatively well explained by inflation expectations and the workforce. Real wages have been flat or declining on average in all economies. The IMF stresses that this is an important aspect of the current economic climate, as falling real wages can have a disinflationary effect, lowering market slack on average, potentially indicating this gradual shift towards more normal economic dynamics. Of course, this shift is highly dependent on whether earlier shocks "retract" and whether "new" shocks emerge.

In addition, the analyzes indicate the key role of the process of shaping expectations in determining wage and price prospects. When wage and price expectations are more retrograde, monetary policy action needs to be more front-on to minimize the risk of inflation becoming de-anchored. As monetary policy is tightened more aggressively and the fall in real wages helps to reduce price pressures, according to the scenario analysis, the risk of a persistent wage-price spiral in the current period is moderately limited, assuming no more persistent inflationary shocks or structural changes in the formation processes of wages and prices (such as a sharp increase in the shift from prices to wages or vice versa).

Determining the optimal response of monetary policy depends on whether the central bank minimizes the welfare function that balances output and inflation deviations or knows the process of shaping expectations and has full information on future cost shocks (IMF 2022).

4. Changes in markups and wages by sector in Poland

Comparing the dynamics of gross markups in the enterprise sector and the CPI in Poland in 2007–2022, it is noteworthy that the dynamics of markups

are usually higher than inflation (CSO 2023). From Q4 2012, when both indices amounted to 3%, there were reverse trends (increasing markups and falling CPI) to Q4 2019 and Q4 2020, when they amounted to 4%. Since Q3 2022, these trends have reversed, with inflation showing a strong increase accompanied by a decrease in gross markups. The growth period of gross markups was from Q3 2021 (3%) to Q2 2022 (8%), followed by a decline to 6% in Q3 2022. If the restrictive impact of the key NBP interest rates and other conditions anti-inflationary measures start to work, a decrease in CPI is expected (Fig. 1).

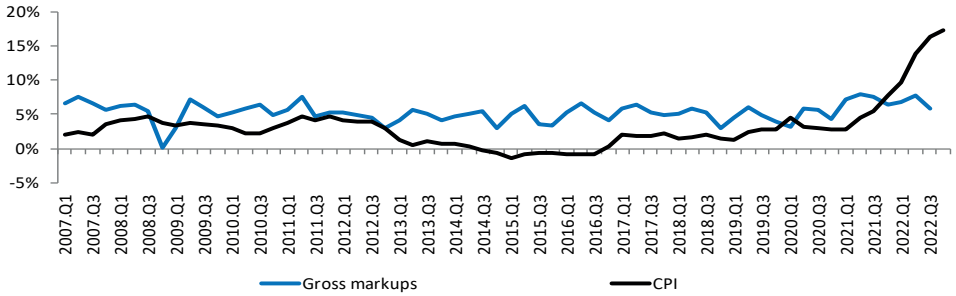

Figure 1. Gross markups in the enterprise sector and CPI in Poland in 2005–2022 [%]

According to the data of the Central Statistical Office for the years 2007–2022, the dynamics of markups in the industry sector (C) in Poland was varied, however, the dynamics of markups in the mining and quarrying section showed the greatest fluctuations. After a decrease in this dynamics in Q2 2020 (–6%), it was later strongly rebounded to 31% in Q2 2022 (which was the effect of the base after the COVID-19 pandemic, as in the situation related to the energy crisis, after the war in Ukraine broke out. Among the other sections of the industry sector, which also achieved high markups, especially in Q2 2021, the following should be noted: water supply, sewage and waste management, reclamation (sectionE) and generation and supply of electricity, gas, and water (section D) showing a decline in subsequent quarters. Among the other sections, high growth (reaching a maximum of 35% in Q1 2021) was recorded in information and communication activities (section J). In Q1 2022, the imposed markups achieved in construction (F) and real estate market services (L) recorded a decrease, rising again in Q2 2022. The volatility of these markups is likely to persist and will depend on changes in supply and employment costs, after on the side of enterprises and on the side of consumers from their income situation (Fig. 2).

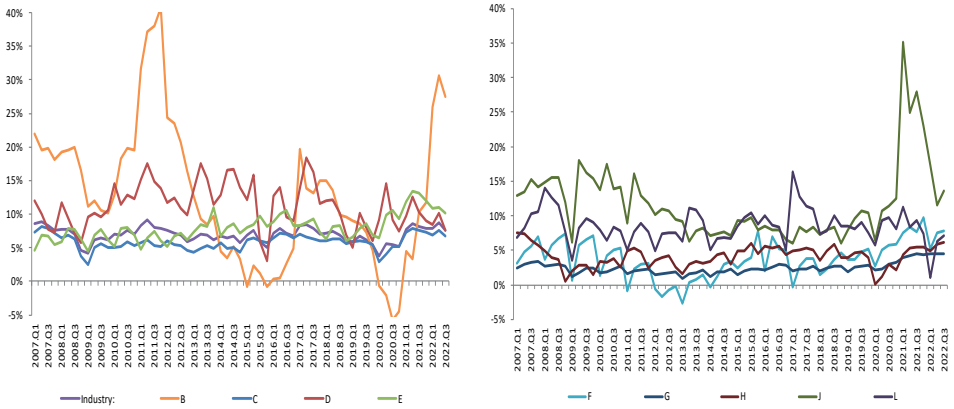

Figure 2. Gross markups in the industry and other sectors in Poland in 2007–2022 [%]

Industry: B – mining and quarrying, C – industrial processing, D – generation and supply of electricity, gas, steam and hot water, E – water supply, sewage and waste management, reclamation and F – construction, G – trade and repair of motor vehicles, H – transport and warehouse management, J – information and communication, L – real estate market service

The growing dynamics of markups was accompanied by an increase in prices for many goods and services, and as a result, it also stimulated an increase in wage pressure in all sectors of the economy. The data of the Central Statistical Office on the dynamics of average monthly gross nominal wages and salaries in Poland in the years 2018–2022 shows that in the case of the enterprise sector, the highest increase in these wages was achieved in the mining and quarrying section (B), i.e. 37% in Q3 2022. The other sections, i.e. industrial processing (C), electricity generation and supply (D) or water supply and sewage and waste management (E), showed significantly lower dynamics. Among the remaining sections, the greatest fluctuations in gross wages and salaries were recorded in health care and social assistance (Q). In the second half of 2022, however, the largest increase in the dynamics of gross fencing was recorded in transport and storage (H), i.e., 27% in Q3 2022 (Fig. 3).

While the dynamics of gross nominal wages in Poland has been increasing since 2017, in 2021–2022, in real terms, their decrease was maintained, a trend clearly discernible from Q3 2021. At that time, the dynamics of real wages in the national economy, as well as in the sector of enterprises employing more than 9 people, amounted to approx. 5%, falling sharply to –1.8% in Q2 2022 in the entire economy and to –4.3% in Q3 2022. The growing disproportion between rapidly growing inflation and falling real wages is noteworthy (Fig. 4).

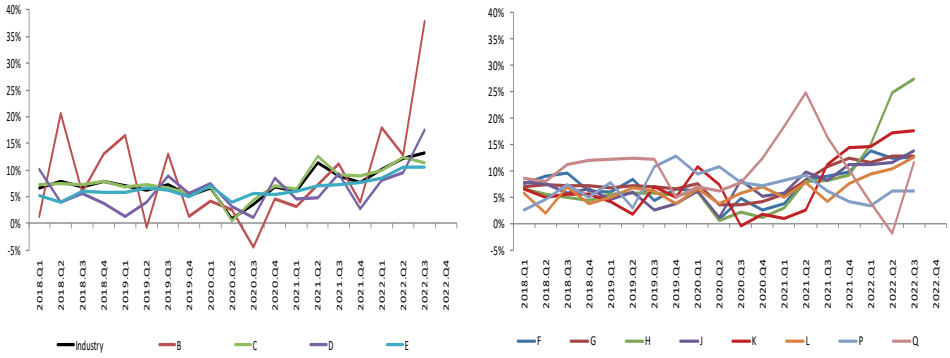

Figure 3. Dynamics of average monthly gross nominal wages in the industry and other sectors in Poland in 2008–2022 [%]

Industry: B – mining and quarrying, C – industrial processing, D – generation and supply of electricity, gas, steam and hot water, E – water supply, sewage and waste management, reclamation and F – construction, G – trade and repair of motor vehicles, H – transport and warehouse management, J – information and communication, L – real estate market service, K – financial and insurance activities, P – education, Q – health care and social assistance

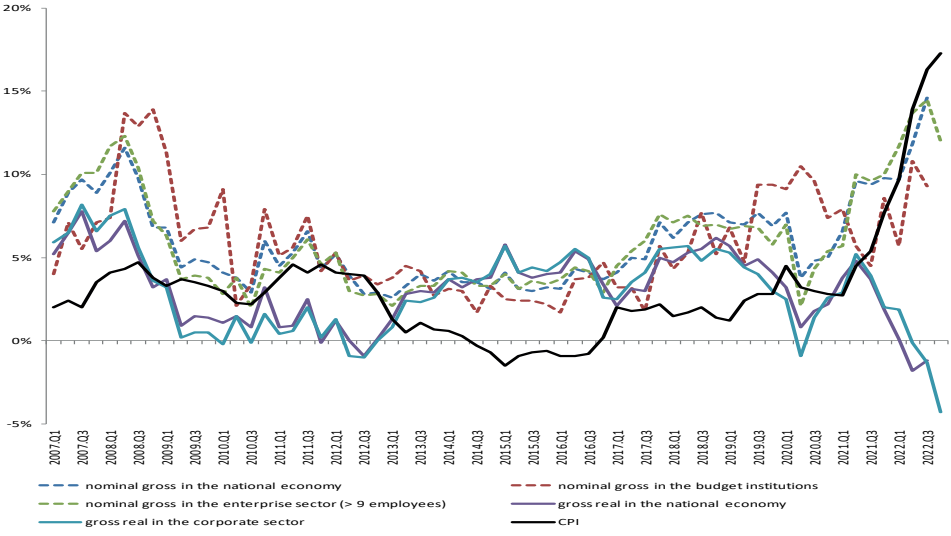

Figure 4. Average monthly nominal and real gross wages and CPI in Poland in 2007–2022 [%]

According to the NBP projections based on the NECMOD (2023) model, in the period 2023–2025 an increase in real wages is expected, with a gradual adjustment of labor costs to the slower rate of economic growth and a moderate increase in unemployment over the forecast horizon.

5. Research methodology

In order to analyze the relationship between changes in CPI and markups and wages in the 2008.Q1-2022.Q4 (60 quarters), a final formula for the CPI function was developed:

$$d\_CPI_t = \propto_0 + \propto_1 d\_Markups_t + \propto_2 d\_Wages_t + \xi_i \quad (1)$$

The explained variable:

d_CPI_t – Consumption Price Index [%].

Explanatory variables:

$d\_Markups_t$ – Gross markups in the economy [%],

d_Wages_t – Gross wages in the economy [%],

ξ_i – random component,

t – period.

Dates came from the CSO database sources. All variables expressed in terms of percent points are included in the form of the first differences variables. Empirical analysis was performed using the eViews11.

The descriptive statistics of the analyzed variables show that in terms of explained variables, markups showed greater variability (St. dev. 0.116, C.V. 199.19, Skewness 1.421 and Ex. kurtosis 3.131) than wages (Tab. 1).

Table 1

Summary Statistics, using the observations 2008:1–2022:4

Variable	Mean	Median	Minimum	Maximum
d_CPI	0.0022373	0.00000	−0.016000	0.042000
d_Markups	−8.0769e-005	0.00041674	−0.052631	0.041484
d_Wages	0.00077586	0.00000	−0.039000	0.031000
Variable	Std. Dev.	C.V.	Skewness	Ex. kurtosis
d_CPI	0.0099805	4.4610	1.4212	3.1310
d_Markups	0.016088	199.19	−0.25327	1.0632
d_Wages	0.013292	17.131	−0.26853	1.0276

Table 1 cont.

Variable	5% Perc.	95% Perc.	IQ range	Missing obs.
d_CPI	−0.010000	0.023000	0.010000	0
d_Markups	−0.026985	0.027678	0.020110	0
d_Wages	−0.024300	0.028100	0.014250	0

Initial data verification concerned the verification of stationarity with the use of several tests. To verify the stationarity of the analyzed time series, the Augmented Dickey–Fuller (ADF) test is used, estimated by means of the regression equation in the following form:

$$\Delta y_t = \mu + \delta_{t-1} + \sum_{i=1}^{k} \delta_i y_{t-1} + \varepsilon_t \tag{2}$$

The value of the test statistic:

$$ADF = \frac{\hat{\delta}}{s(\hat{\delta})}$$

where $\hat{\delta}$ – means the parameter evaluation and $s(\hat{\delta})$ – is the parameter estimate error.

ADF test results confirmed the existence of a unit root a = 1 in the I(1) process and the stationarity of the series.

The lag order for the VAR/VECM model was determined on the basis of estimation of the following information criteria: the Aikake information criterion (AIC), Schwartz–Bayesian information criterion (BIC), and Hannan-Quinn information criterion (HQC). According to these criteria, the best lag order 4 was accepted.

In order to analyze the stability of the VAR model, a unit root test was applied. The test indicates that in the analyzed model equation roots in respect of the module are lower than one, which means that the model is stable and may be used for further analyzes (Fig. 5).

Co-integration was verified using two tests: the Engle-Granger and Johansen tests (Johansen 1991, 1992, 1995). Their results comprehensively confirmed cointegration for lag 4. This is proved by the values of the test statistic τ_e which are lower than critical values $\tau_{critical}$, levels of asymptotic *p*-values and integrated processes.

Results of the Johansen test show that at the significance level of 0.05, cointegration to the order of one occurs. Due to the occurrence of unit element in all the time series and the existence of cointegration between the model variables, it was possible to extend and transform the model into vector error correction models (VECM).

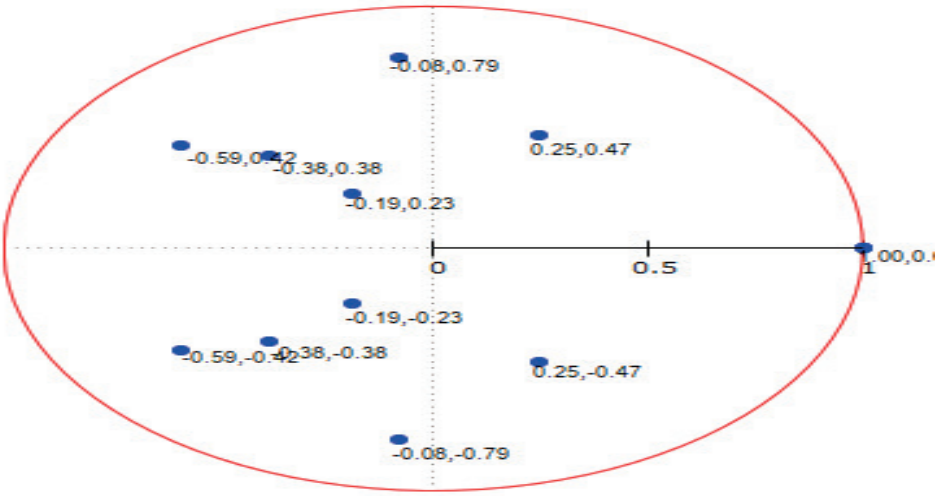

Figure 5. VAR inverse roots in relation to the unit circle

6. Empirical model

6.1. VECM model

Co-integration was verified by means of the Engle-Granger and Johansen tests which confirmed the occurrence of co-integration and thus justified the use of the VECM model for the lag order 1 and co-integration of order 1. In accordance with the Granger representation theorem, if variables y_t and x_t are integrated to the order of I (1) and are co-integrated, the relationship between them can be represented as a vector error correction model (VECM).

The general form of the VECM can be written as:

$$\begin{aligned} \Delta Y_t &= \Gamma_1 \Delta Y_{t-1} + \Gamma_2 \Delta Y_{t-2} + \ldots + \Gamma_{k-1} \Delta Y_{t-k+1} + \pi Y_{t-k} + \varepsilon_t = \\ &= \sum_{i=1}^{k-1} \Gamma_i \Delta Y_{t-i} + \pi Y_{t-k} + \varepsilon_t \end{aligned} \tag{3}$$

where:

$$\Gamma_i = \sum_{j=1}^{i} A_j - \mathrm{I},\ i = 1, 2, \ldots, k-1, \quad \Gamma_k = \pi = -\pi(1) = -\left(\mathrm{I} - \sum_{i=1}^{k} A_i \right)$$

and I is a unit matrix.

Table 2

VECM system

	beta (cointegrating vectors, standard errors in parentheses)		alpha (adjustment vectors)	
d_CPI	1.0000	(0.00000)	−0.038392	
d_Markups	−19.858	(3.3527)	0.12188	
d_Wages	−4.1164	(1.8425)	−0.0070512	
Equation 1: *d_d_CPI*	Coefficient	Std. Error	*t*-ratio	*p*-value
const	0.000802175	0.00122416	0.6553	0.5158
EC1	−0.0383920	0.0201011	−1.9100	0.0628*
R-squared	0.369592	Adjusted R-squared	0.222985	
rho	−0.049353	Durbin–Watson	2.081440	
Equation 2: *d_d_Markups*	Coefficient	Std. Error	*t*-ratio	*p*-value
const	0.000917658	0.00140464	0.6533	0.5170
EC1	0.121885	0.0230648	5.2840	<0.0001***
R-squared	0.825057	Adjusted R-squared	0.784373	
rho	−0.071169	Durbin–Watson	2.028696	
Equation 3: *d_d_Wages*	Coefficient	Std. Error	*t*-ratio	*p*-value
const	0.00124978	0.00190912	0.6546	0.5162
EC1	−0.00705120	0.0313486	−0.2249	0.8231
R-squared	0.591495	Adjusted R-squared	0.496494	
rho	−0.006118	Durbin–Watson	1.938970	

Note: Lag order 4, maximum likelihood estimates, observations 2009:2–2022:3 (T = 54), cointegration rank = 1; * $p < 0.1$, *** $p < 0.01$.

The evaluation of the vector correction model component (EC1) representing the mechanism of short-term adjustments which serves the attainment of the long-term model balance (Tab. 2). Evaluation of the EC1 indicates that the strongest correction of the deviation from long-term equilibrium occurs in the case of the markups. Here, around 1.2% of the imbalance from the long-term growth path is corrected by a short-term adjustment process. Weaker deviation adjustments occur for CPI from wages (−0.7%). The values of the coefficient of determination R^2

reveal adjustment matching of the VECM model equations to empirical data, i.e., for CPI (22.3%), markups (78.4%) and wages (49.6%).

To verify the correctness of the VECM model results, the ARCH test was carried out verifying occurrence of autocorrelation. The ARCH test results indicate that in the examined model of the residual-based process (three variables), the ARCH effect was not observed because LM test statistics are lower than the levels of χ^2. This means that there is no autoregressive changeability of the conditional variance and there is no need to estimate model parameters by means of weighted least squares method. Thus, the results of this test confirm the credibility of the VECM model and allow for conclusions to be drawn on their basis.

6.2. The impulse response functions and the variance decomposition

Analysis of CPI responses to shocks derived from markups and wages reveal that CPI responses are the strongest to impulses from markups and weaker form wages. However, CPI responds positively to both shocks. The responses of CPI were strongest from own past shocks, stabilizing after period 4. The impact of markups on CPI responses weakened 0.27% in period 2 to 0.11% in period 20 and increasing in response to wage changes (0.03% and 0.07%). The reaction of the CPI impulse response was longer on the side of markups (stabilizing after 15 periods) and shorter and weaker on the part of wages (stabilizing after 7–10 periods) (Fig. 6).

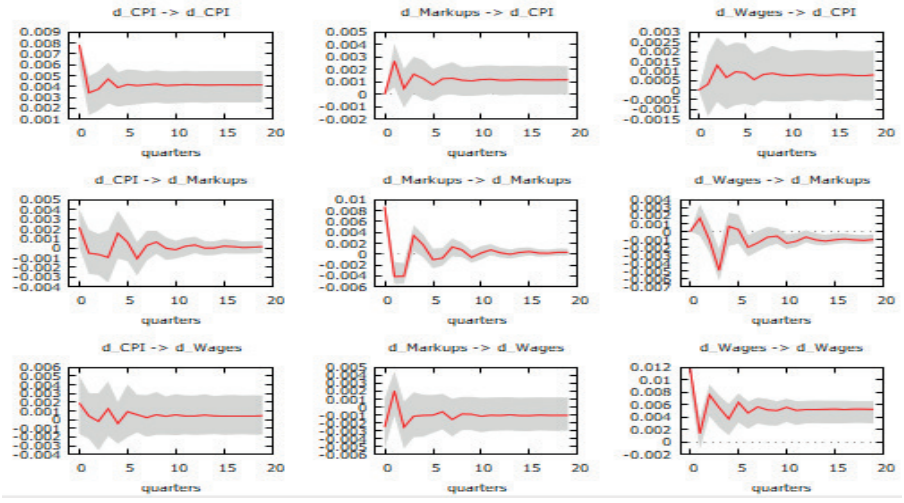

Figure 6. Impulse responses to a one-standard error shock in CPI, markups, and wages

CPI, markups, and wages were analyzed by means of variance decomposition in the forecast horizon of 20 quarters (5 years). Results of CPI decomposition indicate that in the period 1 these changes are fully accounted for with their own forecast errors. In period 2, their own changes lose (91.0%) and such markups (8.9%) and wages (0.1) grow in significance. In the period 20 CPI's own changes decrease to 89.7% and increase the degree of its explanation by markups (7.4%) and wages (2.9%).

The importance of markups in explaining changes in CPI decreases over time (from 8.9% in period 2 to 7.4 in period 20) and increases in wages (from 0.1% in period 2 to 2.9% in period 20). It is worth noting that over the forecast period, the degree of explanation of CPI on the part of markups remains 2–3 times higher than wages. However, the degree of explanation of CPI depended mainly on own shocks, although they show a certain decrease (100.0% and 89.7%).

The decomposition results for markups and wages indicate that their changes depend on their previous own changes. However, during the change of markups, it depends more on wages (from 2.8% in period 2 to 25.5% in period 20) than results of wages decomposition on the part of markups (from 4.3% in period 1 to 5.1% in period 20) (Tab. 3).

Table 3

Decomposition of variance for CPI, markups, and wages in the 20 periods

	for *d_CPI*			for *d_Markups*			for *d_Wages*		
period	*d_CPI*	*d_Mark-ups*	*d_Wages*	*d_CPI*	*d_Mark-ups*	*d_Wages*	*d_CPI*	*d_Mark-ups*	*d_Wages*
1	100.0000	0.0000	0.0000	5.7638	94.2362	0.0000	2.4625	4.3182	93.2193
2	91.0013	8.8825	0.1163	4.8801	92.2917	2.8283	2.4741	6.7836	90.7424
3	90.5639	7.6235	1.8126	4.4923	92.0865	3.4212	1.7691	7.7933	90.4376
4	89.9924	8.2168	1.7908	4.0182	77.8132	18.1686	2.1547	7.3058	90.5395
5	89.4622	8.3272	2.2107	5.3610	76.8578	17.7812	2.1093	7.3186	90.5721
6	89.8565	7.6826	2.4609	5.5400	76.8040	17.6560	2.0829	6.6618	91.2553
7	89.8656	7.7622	2.3723	6.0523	74.4948	19.4529	2.0422	6.3256	91.6322
8	89.6911	7.8389	2.4700	5.9596	73.8235	20.2169	1.8652	6.4160	91.7187
9	89.6957	7.7113	2.5929	6.1394	73.5214	20.3392	1.8140	6.1627	92.0233
10	89.7555	7.5980	2.6465	6.1143	73.4313	20.4543	1.7336	5.9762	92.2902
11	89.7511	7.5813	2.6677	6.0506	72.4998	21.4496	1.6775	5.8494	92.4731
12	89.7200	7.5777	2.7023	5.9976	71.9640	22.0385	1.6175	5.7462	92.6364
13	89.7276	7.5155	2.7569	6.0348	71.7340	22.2312	1.5588	5.6419	92.7993

Table 3 cont.

	for *d_CPI*			for *d_Markups*			for *d_Wages*		
period	*d_CPI*	*d_Markups*	*d_Wages*	*d_CPI*	*d_Markups*	*d_Wages*	*d_CPI*	*d_Markups*	*d_Wages*
14	89.7474	7.4718	2.7809	5.9973	71.2886	22.7141	1.5247	5.5172	92.9581
15	89.7413	7.4607	2.7980	5.9456	70.7295	23.3249	1.4803	5.4445	93.0753
16	89.7328	7.4414	2.8258	5.9241	70.3244	23.7515	1.4417	5.3747	93.1837
17	89.7397	7.4103	2.8500	5.9065	69.9831	24.1103	1.4093	5.2945	93.2962
18	89.7447	7.3888	2.8665	5.8717	69.5624	24.5660	1.3791	5.2284	93.3924
19	89.7417	7.3770	2.8812	5.8322	69.1041	25.0638	1.3516	5.1717	93.4767
20	89.7408	7.3608	2.8985	5.8083	68.7307	25.4609	1.3247	5.1191	93.5562

7. Conclusion

The analysis of the theoretical and empirical literature indicates various determinants of inflation which may be of a supply and demand nature. A decrease in the supply of non-wage inputs causes costs to increase. However, increases in aggregated demand cause an growth in demand for: goods and services, inputs and labor affect on demand-pull inflation.

The growing various effects of the COVID-10 pandemic, the outbreak of war in Ukraine and the aftermath of the energy crisis are responsible for both supply- and demand-type stimuli, making it difficult to lower both inflation and inflation expectations. Enterprises try to hedge against inflation, e.g., in the form of raising markups and employees in the form of wage increases to compensate for the decline in the purchasing power of nominal wages.

The results of empirical and econometric analyzes allowed the formulation of the following conclusions for Poland.

1. In the years 2007–2022, markups showed a higher dynamic of change than wages.
2. In terms of the dynamics of markups and wages, the highest dynamics was achieved by the industry sector, including the mining and quarrying section (B). High dynamics of markups, apart from mining, was shown in the section of water supply, sewage and waste management, reclamation (section E) and electricity, gas and water production and supply (section D). Among the remaining sections, activity in the field of information and communication

(section J) recorded a high increase. In the case of wage dynamics, sections of transport and storage (H) and health care (Q) were characterized by high dynamics.

3. Analysis of CPI responses to shocks derived from markups and wages reveal that CPI responses are the strongest to impulses from markups and weaker from wages. However, CPI responds positively to both shocks. The responses of CPI were strongest from own past shocks, stabilizing after period 4. The impact of markups on CPI responses was weakening (0.27% in period 2 to 0.11% in period 20) and increasing in response to wage changes (0.03% and 0.07%). The response of the CPI impulse response was longer on the part of markups (stabilizing after 15 periods) and shorter and weaker on the part of wages (stabilizing after 7–10 periods)
4. Results of CPI decomposition indicate that these changes are fully accounted for with their own forecast errors in period 1. In period 2, their own changes lose (91.0%) and such markups (8.9%) and wages (0.1) grow in significance. In period 20, the CPI's own changes decrease to 89.7% and increase the degree of its explanation by markups (7.4%) and wages (2.9%). Moreover, the importance of markups in explaining CPI changes decreases over time (from 8.9% in period 2 to 7.4 in period 20) and increases in wages (from 0.1% in period 2 to 2.9% in period 20). Moreover, in the forecast period (20 periods, 5 years), the degree of CPI explanation on the part of markups remains 2–3 times higher than wages.
5. The results of the decomposition for markups and wages indicate, in the forecast period (20 periods), that their changes mainly depend on their own earlier changes. However, over time, markups changes may depend more on wages (from 2.8% in period 2 to 25.5% in period 20) than results of wages decomposition on the part of markups (from 4.3% in period 1 to 5.1% in period 20). This means the expected increase in the importance of wages.

The disproportion between rising inflation and falling real wages presented in Figure 4 means that in the short and medium term the need to rebuild the real purchasing power of wages will be accompanied by wage pressure. The wage pressure will continue, at least until the upward dynamics of inflation stops. In addition, it is worth emphasizing that unfavorable democratic changes in Poland (low birth rate, fewer and fewer new people entering the market at working age) may contribute to maintaining the upward trend in wages.

Summing up, the presented results of empirical research indicate a positive verification of the hypothesis and allow us to conclude that "The increase in inflation expectations and future production costs in the economy stimulated the growth of enterprise markups, limiting the effectiveness of anti-inflation measures in Poland at the turn of 2007–2022, with the expected stronger impact of wages in subsequent years, in accordance with the variance decomposition."

8. Study limitations and directions for the further research

The study has some limitations. First, the period of maintaining exogenous shocks and their intensification at the time of destabilizing efforts of anti-inflation policy in Poland and in the world. The second, the consolidation of inflation expectations at a high level, both on the side of enterprises deciding, for example, to change markups or employees who pass wage increases. The third, the effects of the fight against inflation are determined by the total decisions made as part of fiscal policy. Thus, it requires complementary decisions within the policy mix, especially in the period of problems with fighting high inflation.

In future surveys, an important issue is the study of the impact of monetary policy tightening on changes in inflation expectations as well as the effects of changes in the distribution of income in the economy, i.e. socio-economic consequences. The effects of high inflation are more pronounced for low-income households. The global negative price shock following the Russian aggression in Ukraine had heterogeneous inflationary effects across EU countries and households.

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Summary

This paper analysis of the impact of markups and wages of enterprises on changes in the level of inflation in Poland in the years 2007–2022. The impact of markups and wages on changes in CPI were assessed using the VECM model, the impulse responses, and the variance decomposition. The results indicate that industrial sector, including the mining and quarrying section, showed the highest dynamics of changes in markups and wages. In the years 2005–2022, the impact of markups on changes in CPI was stronger, although it was losing importance, with a weaker but growing impact of wages. Forecasts of the degree of clarification of the CPI in Poland indicate a greater importance of markups, with the impact of wages weaker by half, but growing over time. The paper extends the state of theoretical and empirical studies on the determinants of the CPI and the inflation expectations. It also considers the context of persistent exogenous and endogenous shocks from the COVID-19 pandemic and the war in Ukraine, and changes in demand and supply impulses. The results of this study may be valuable as a contribution to the literature on inflation and its forecasts, and for monetary policy makers.

*JEL codes***:** E52, E58, E63, E66

Keywords: *inflation expectations, inflation, markups, wages*

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Jan Koterwa*, Hubert Kycia**,
Anna Czapkiewicz***

The relationship between the inflation rate and the unemployment rate in Poland and their long-term associations with selected macroeconomic variables

1. Introduction

Analyzing the relationship between macroeconomic and financial variables has been popular in the scientific world in recent years. Numerous works have been written in which authors have shown the existence of significant short- and long-term relationships between macroeconomic factors.

Based on empirical data from the period 1861–1957 from the United Kingdom, Philips (1958) demonstrated the existence of a negative correlation between the unemployment rate and the pace of wage growth. As a result of this study, the Phillips curve was developed, illustrating the statistical relationship between the unemployment rate and inflation. The theory was challenged by the phenomenon of stagflation, which involves the simultaneous occurrence of high unemployment and inflation rates. This phenomenon occurred in Western European countries and the USA after the first oil crisis in 1973.

Phelps (1968) illustrated that in cases where the unemployment rate is low, achieving equilibrium between unemployment and inflation rates is impossible. In the event of increased money supply, this leads to the occurrence of hyperinflation without affecting the unemployment rate.

In contrast, L.P. Rochon and S. Rossi (2018), rejecting the above theories, point out that the unemployment rate and the inflation rate are linked through the

* AGH University of Krakow, Krakow, Poland, e-mail: jankoterwa@student.agh.edu.pl
** AGH University of Krakow, Krakow, Poland, e-mail: kyciahubert@student.agh.edu.pl
*** AGH University of Krakow, Krakow, Poland, e-mail: gzrembie@cyf-kr.edu.pl

mechanism of the actions of banks' in the credit market. When commercial banks provide lines of credit for non-GDP transactions, they inflate the volume of bank deposits without primary purchasing power. This is instrumental in increasing the price of assets, and it indirectly translates into an increase in unemployment when deposit holders choose to purchase real estate or financial assets (the prices of which rise as a result of this inflationary pressure), rather than allocating their income to goods and services on the market. Such action translates into a reduction in the level of employment in many companies, which do not increase their revenues in such a situation.

The aim of this paper is to analyze the long- and short-term dependencies for selected Polish macroeconomic factors in the period 2001–2021. The analysis considers the WIG20 index, the USD/PLN exchange rate, the Brent crude oil index, the interest rate on 10-year treasury bonds, inflation, and the unemployment rate. The correlation between inflation and unemployment was analyzed thoroughly. It was also examined whether the relationship between the inflation rate and the unemployment rate in the Polish economy can be described with the use of the Phillips curve.

The authors' justification for choosing such a research topic was the current economic situation in Poland and the fact that from February 2021 to February 2023, the annual inflation rate increased from 2.4% to the level of 18.4%. This was the second-highest inflation rate in the European Union after Hungary. The inflation rate significantly affects the standard of living of Poles in the country, initiating a lively discussion about the factors influencing inflation and strategies to mitigate it.

This paper consists of the following sections: in the second part, a literature review is presented. Section three covers the methodology and the description of tools and tests used while the fourth part covers the presentation of the study results and their interpretation. The paper concludes with a brief summary and description of the conclusions.

2. Literature

There are numerous studies about the relationship between macroeconomic variables in different countries in the literature. I.O. Osamwonyi and E.I. Evbayiro-Osagie (2012) showed the existence of significant short-run and long-run relationships between the Nigerian stock market index and the inflation rate in Nigeria. E. Lawal (2016), on the other hand, in his study reported the absence of long-run relationships between the inflation rate and the Nigerian stock market index.

This implies that a study conducted for the same country's economy may lead to divergent results, which may be the effect of using data from different periods or selecting other econometric models.

Naka et al. (1998) performed a similar analysis for data describing the Indian economy. The paper shows that selected macroeconomic variables, including the inflation rate, are in a long-run relationship with the Indian stock market index. Studies focusing on the relationship between macroeconomic variables and stock market indices have also been conducted by: Gjerde and Saettem (1999) for the Norwegian economy, M. Ibrahim (1999) for the Malaysian economy, T. Barbic and I. Condic-Jurki (2011) for the economies of selected Central and Eastern European countries, Maysami et al. (2004) for the Singapore economy and many others.

Another example of an analysis of macroeconomic processes based on the VECM model is the work of Asari et al. (2011), which examined the relationships between interest rates, inflation, and exchange rate volatility in Malaysia. Andrei (2015) examined the relationship between macroeconomic variables for the Romanian economy, while Nsabimana et al. (2020) verified the relationship between sustainable investment and economic growth in China. Wojciechowski (2015) analyzed the hypothesis on the impact of international trade openness on productivity acceleration. The results of the study conducted, for the Visegrad Group, indicate that there is a long-term relationship between economic openness and labor productivity for all V4 countries, with unidirectional causality in the Granger sense running from productivity to trade openness in the case of Hungarian economy. In contrast, an article by Hülsewig et al. (2001) investigates the impact of the bank lending channel on the transmission mechanism of monetary policy in Germany. With the use of VECM model, authors obtained two cointegrating relationships interpreted as the supply and demand of long-term credit. It was observed that monetary policy has a negative impact on both the supply and demand of long-term credit. At the same time, the authors found that this impact is quite weak due to the protection that banks surround their customers when the state applies restrictive monetary policy.

One example of the application of multivariate models to the Polish economy is the work of M. Salamaga (2015), in which the author examines the long-run relationship between exports and the pattern of comparative advantage. Based on the VECM model constructed, the existence of a long-run equilibrium state is shown. A. Marona and B. Bieniek (2013) conducted a study describing the impact of foreign direct investment on the Polish economy. An article on a similar topic by H. Gurgul and Ł. Lach (2009) shows results indicating significant relationships between direct investment and economic growth in Poland. The existence of these relationships was confirmed in a paper by L. Wojciechowski (2016), which

also shows that the HICP inflation rate, fixed capital formation, and the nominal effective exchange rate have a significant impact on the productivity of the Polish economy. A. Geise (2015) examined how Brent oil price developments affect the inflation rate in selected EU countries. The results indicate that the inflation changes due to an oil shock are of a permanent nature, meaning that these shocks do not wear off. A. Czapkiewicz and M. Stachowicz (2016) show that variables such as the Polish inflation rate, the Polish stock market index, and the EUR/PLN exchange rate are in long-run equilibrium.

3. Methodology

3.1. VECM

The VECM model allows both short- and long-term dynamics to be analyzed. The general form of the VECM model consisting of K endogenous variables is given by equation (1) (Johansen 1995).

$$\Delta y_t = \pi y_{t-1} + \sum_{i=1}^{p} \Gamma_i \Delta y_{t-i} + u_t \tag{1}$$

where:

$\pi = \alpha\beta'$
where:
α – matrix of variable adjustment coefficient to the equilibrium state,
β – matrix of long-run coefficients of cointegrating relationships,
Γ_i – matrixes of coefficients of autoregressive successive lags (short-run dynamics),
p – lag order,
u_t – random disturbances.

The rank of π matrix is equal to the number of cointegrating relationships r. Depending on the value of r, the appropriate form of the model should be adopted:

- $r = 0$ – no cointegration, VAR model is constructed on differenced variables,
- $r = 1, \ldots, K - 1$ – cointegration exists, VECM model is constructed on differenced variables,
- $r = K$ – no cointegration, VAR model is constructed as the variables are stationary.

The verification of the number of cointegrating relationships is equivalent to determining the rank of π matrix. S. Johansen (1991, 1992) proposed two methods

to test the cointegration rank: the trace statistic (2) and the maximum eigenvalue test (3). The null hypothesis of Trace test states that $rank(\pi) \leq r_0$ and the alternative hypothesis states that $rank(\pi) > r_0$. The null hypothesis of maximum eigenvalue test states that $rank(\pi) = r_0$ and alternative hypothesis suggests that $rank(\pi) = r_0 + 1$.

$$\lambda_{tr}(r_0, K) = -T \sum_{i=r_0+1}^{K} \log(1 - \lambda_i) \tag{2}$$

$$\lambda_{\max}(r_0, r_0 + 1) = -T \log(1 - \lambda_{\max}) \tag{3}$$

where λ_i are the eigenvalues of π matrix and values are organized in ascending order. Testing begins with the null hypothesis $rank(\pi) = 0$ and is carried out iteratively until there are no grounds to reject the null hypothesis.

Both Johansen tests and VECM model require the determination of the optimal lag order. For this purpose, the values of the information criteria are used: Akaike information criterion (AIC), Hannan–Quinn information criterion (HQC), Schwartz criterion (SC), Final Prediction Error criterion (FPE).

3.2. Impulse response function

One of the key issues related to the VECM model is that it is possible to analyze the impact of a single variable on other variables, with the aim of discovering economic relationships in both the short and long term. Impulse response function can be used to perform this analysis. Its form is described by equation (4).

$$y_t = \mu + \sum_{i=0}^{\infty} \Theta_i \omega_{t-i} \tag{4}$$

where:

$\mu = E(y_t)$,
$\Theta_i = \Phi_i P$,
$\omega_t = P^{-1} u_t$,
u_t – random disturbances,
p – the lower triangular matrix obtained based on the Cholesky decomposition of the covariance matrix of random disturbances.

In practice, it is assumed that the forms of matrices Θ_i and Φ_i are not known, so they are calculated based on the obtained estimates of the VECM model parameters and the covariance matrix of errors (Lütkepohl 2005). In this case, the Φ_i matrix is described by equation (5).

$$\Phi_i = \sum_{j=1}^{i} \Phi_{i-j} A_j, \quad i = 1, 2, \ldots, \tag{5}$$

where A_j – matrices of autoregressive coefficients and $A_j = 0$ for $i > j$.

If $i = j$ then $\Phi_{i-j} - \Phi_0$ and it is assumed that this matrix is the identity matrix I_k of order $k \times k$. The coefficients of Φ_i matrix are interpreted as the responses of any variable in the vector y_t to an impulse from another variable in this vector, assuming the constancy of the remaining factors (Salamaga 2015). The Θ_i matrix is defined by the following equation (6).

$$\Theta_i = \Phi_i P \tag{6}$$

where p – similarly, as in the equation (4).

3.3. Variance decomposition

The analysis of the influence of individual variables on other variables in the model can be extended based on the decomposition of the forecast error variance. The Forecast Error Variance Decomposition (FEVD) informs to what extent the variance of an endogenous variable is explained by the remaining variables in the model. The formal expression for the magnitude of the forecast error variance of variable j explained by exogenous shocks of variable k for forecast horizon h at forecast origin t is determined by the formula (7).

$$\omega_{jk,h} = \frac{\sum_{i=0}^{h-1} (e_j' \Theta_i e_k)^2}{MSE\left[y_{j,t}(h) \right]} \tag{7}$$

where e_j – j-th column of the matrix I_k, where the index jj specifies the element of this matrix.

The denominator of the fraction is the mean squared error for the h-th step forecast, for variable j. It is described by equation (8).

$$MSE\left[y_{j,t}(h) \right] = \sum_{i=0}^{h-1} (\Phi_i \Sigma_u \Phi_j')_{jj} \tag{8}$$

where:

Σ_u – the covariance matrix of the random component of the VECM model,
$\Phi_i = JA^j J', J = \left[I_k, 0, \ldots, 0 \right]$, matrix J is of order $kxkp$,
p – number of lags in the model.

4. Empirical study

4.1. Dataset description

The study was conducted for monthly data describing selected macroeconomic processes in Poland from 2001 to 2022. Six variables were chosen:

- Inflation (percentage change compared to the same month of the previous year),
- Unemployment,
- WIG20 (Polish stock market index),
- USD/PLN exchange rate,
- Long-term government bond yields (LTI),
- Brent Crude Oil Index.

The choice of the above variables is justified by the fact that the first five of them are interconnected and shape the economic situation in Poland. The Brent oil index was included in the set of variables because Geise hypothesized in his work about the existence of a relationship between oil prices and inflation, which has a transmission character. Based on the research results, the author concluded that this hypothesis is true.

Data was collected from Eurostat, as well as from databases on the stooq.pl and investing.com websites. Figure 1 depicts line charts of these variables.

Maintaining the inflation rate below 5% for nearly two decades until the beginning of 2021 is considered one of the major successes of Poland's socio-economic transformation. As of July 2000, the inflation rate was at 11.6%, while the unemployment rate, which had increased due to structural changes in the Polish economy, stood at 16%. Thanks to a restrictive monetary policy applied in 2001–2003, the inflation rate dropped to 1.6% in December 2003. However, this decline in inflation had an impact on the unemployment rate, which in the same month reached 19.8%. This means that after a period of stagflation, there was an inverse relationship between inflation and unemployment in accordance with the Phillips curve. Poland's entry into the European Union allowed the country to access new investment funds and gain new markets for Polish businesses, although they also faced new competitors. Opening up the Polish market to foreign economic entities also had positive effects, as it led to the creation of new job opportunities. Thanks to these factors, as well as favorable changes in the Labor Code introduced in 2002 and the emigration of some unemployed individuals to EU countries, the unemployment rate dropped below 10% in May 2007, for the first time since May 1998 (Bolejko et al. 2014). Due to the outbreak of the financial crisis, the unemployment rate exceeded 10% once again. However, the growth of

unemployment was curbed in 2013, and since then, there has been a consistent decline, driven by a favorable economic climate that lasted until the outbreak of the COVID-19 pandemic.

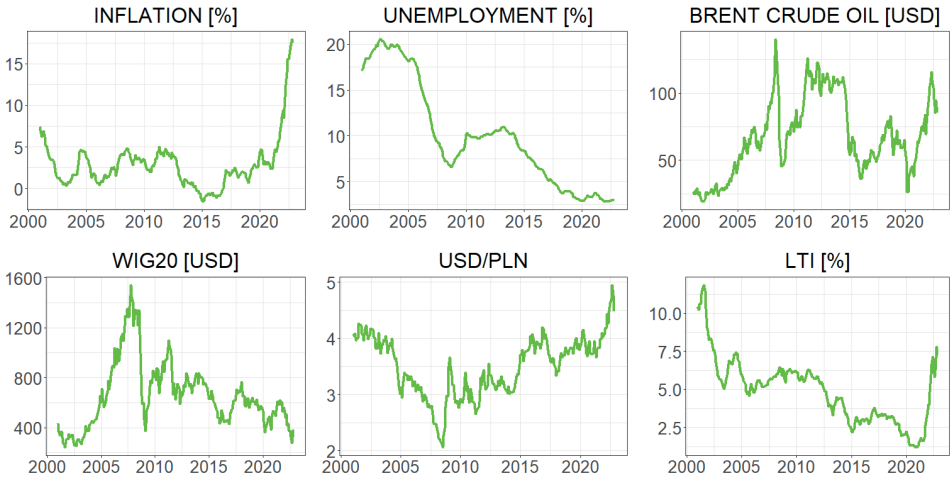

Figure 1. Line charts of the selected macroeconomic processes

The economic recession resulting from the outbreak of the COVID-19 pandemic led to an increase in the inflation rate, which reached 5% in July 2021. Since then, there has been a sharp rise in inflation. In November 2022, the inflation rate stood at 17.1%, the highest level since February 1997. Several reasons for this situation can be identified:

- The economic recession was caused by the need to impose restrictions in many areas of social and economic life. Due to lockdown measures, economic demand was limited, leading to wage reductions and job cuts. Supply, on the other hand, was hindered due to the temporary suspension of operations by some businesses, a reduction in the supply of raw materials from abroad, and increased employee absenteeism resulting from the "zero COVID" policy (Santander Bank Polska 2020).
- The National Bank of Poland's (NBP) initial reluctance to raise interest rates during the early stages of inflation growth, which contributed to further inflationary pressure.
- The government's support for Polish companies through financial aid packages in the form of anti-crisis shields.

- The rapid increase in oil prices in 2020–2021 led to a weakening of PLN against USD, along with additional cost increases for businesses in various sectors, especially in the fuel, energy, construction, and transportation industries.
- The outbreak of the war in Ukraine in February 2022 and the subsequent embargo on Russian goods, along with investor uncertainty about the geopolitical situation in the region, partially limited investments, especially in the commercial real estate market (Mirowski 2022).

The global financial crisis in 2007–2008 had a negative impact on the WIG20 index, which, after a sharp decline in value in 2008, never returned to the levels seen in 2005–2007. Currently, the values achieved by the WIG20 are similar to those recorded at the beginning of the 21st century.

The situation is somewhat different in the case of the Brent Crude Oil index. After a 70% drop caused by the financial crisis in 2007, the price of an oil barrel reached 125 USD as early as April 2011. It remained relatively stable until the autumn of 2014 when it started to decline sharply due to factors such as the oil war among OPEC countries, the appreciation of USD, the emergence of the Islamic State, and the outbreak of conflict in eastern Ukraine. The period of falling oil prices ended with the outbreak of the COVID-19 pandemic, which significantly weakened the U.S. and global economies, contributing to a rapid increase in the price of a barrel of oil. Currently, it is at a similar level as it was before 2014.

Due to the nature of fluctuations in the exchange rate of USD against PLN within the analyzed time frame, three periods can be distinguished:

- In the first period, from 2001 to 2003, the exchange rate of USD against PLN remained stable. This situation was due to the weakening of USD and a decrease in inflation in Poland.
- From 2004 to 2007, there was a continuous decline in the value of USD against PLN, driven by increased exports and foreign capital inflow after Poland's accession to the EU. This led to the appreciation of PLN against USD, in line with the Balassa-Samuelson effect.
- Since 2008, the exchange rate of USD against the PLN has shown an upward trend (Gadomski 2019).

After the inflation rate stabilized at the beginning of the 21st century, the interest rate on long-term government bonds was at a level close to the inflation rate. The increase in inflation in 2021 has also caused the LTI to rise, however this is less than the increase in the inflation rate. Interest rates need to be raised gradually so that the increase in the cost of servicing loans is less steep, hence the difference between the LTI and the inflation rate seen at the end of 2021.

4.2. VECM model estimation

The first stage of the conducted research involved testing the stationarity of the time series under consideration. The augmented Dickey-Fuller test at a significance level of 5% indicated that all variables are non-stationary. Subsequently, the ADF test was repeated for the first differences of the data series according to formula (9)

$$\Delta y_t = y_t - y_{t-1} \quad \left(t \in T_1\right), \tag{9}$$

where $T_1 = \{1, 2, \ldots, n-1\}$.

It transpired that for each analyzed variable, its first differences, based on the ADF test results, could be considered as a stationary series. Detailed results of the ADF tests are presented in Table 1.

Table 1

P-values of the ADF test for the considered time series

Variable	P-value	Conclusion
Inflation	0.99	Non-stationary
Unemployment	0.97	Non-stationary
USD/PLN	0.53	Non-stationary
Brent oil	0.58	Non-stationary
WIG20	0.62	Non-stationary
LTI	0.99	Non-stationary
Inflation	<0.01	Stationary
Unemployment	<0.01	Stationary
USD/PLN	<0.01	Stationary
Brent oil	<0.01	Stationary
WIG20	<0.01	Stationary
LTI	<0.01	Stationary

In order to construct the VECM (Vector Error Correction Model), the optimal number of lags was selected. The choice was made based on four information criteria: HQ, AIC, BIC, and FPE. Based on the selected information criterion, the optimal lag order was determined to be one.

The existence of cointegrating relationships was verified with the use of the Johansen trace test (1988). One cointegrating relationship was detected, described by equation (10).

$$Inflation_t + 1.667 \cdot Unempl_t + 0.035 \cdot WIG20_t + \\ - 0.756 \cdot USDPLN_t - 0.175 \cdot Brent_t - 5.159 \cdot LTI_t = \varepsilon_t \quad (10)$$

The above equation represents a long-term equilibrium between the inflation rate and the other variables. This equilibrium is a system of interrelated variables that adjust to each other in such a way that there is no predominant tendency to change the state of the system in the model they form. Since all the series composing the variables are $I(1)$, this equilibrium is a static equilibrium, implying the stationarity of all the variables constituting the system (Welfe 2020).

The coefficients of the variables in equation (10) form a cointegrating vector, defining the long-term relationship between the variables. The reference point is the variable describing inflation, for which the coefficient β takes the value of 1. An increase in the unemployment rate by one percentage point is associated with a increase in the inflation rate by more than one percentage point. This long-term interdependence between inflation and unemployment aligns with current economic theory. An increase in the WIG20 index is associated with an increase in inflation, while the growth of the USD/PLN, Brent, and LTI variables is correlated with a decrease in inflation.

Table 2 shows the estimated parameters of the individual equations of the VECM model, the number of individual equations corresponds to the order of variables in the cointegrating vector. The parameter α appearing in all equations is interpreted as the rate of adjustment of the variable to the equilibrium state. If the variable has a positive sign at β in the long – run relationship, then a negative value of α indicates that the variable returns to equilibrium in subsequent periods. If α is positive, then the variable moves away from equilibrium in subsequent periods. It follows that unemployment returns to equilibrium at a slow rate, while the interest rate on long-term government bonds moves away from equilibrium at a slow rate. The other parameters of α are not significant.

Table 2

Coefficients of VECM model parameters

Equation	α_i	$\Delta y_{1,t-1}$	$\Delta y_{2,t-1}$	$\Delta y_{3,t-1}$	$\Delta y_{4,t-1}$	$\Delta y_{5,t-1}$	$\Delta y_{6,t-1}$
I	−0.004	0.335**	−0.303	0.000	0.902**	0.021**	0.049
II	−0.005**	−0.026	0.601**	−0.000	−0.059	0.000	−0.000
III	−0.311	−24.07*	−32.96	0.007	−19.10	1.113	24.93
IV	0.001	0.040*	0.063	−0.000	−0.074	−0.001	−0.071*
V	0.076	−1.378	1.652	0.017	5.712	0.237**	1.922
VI	0.005*	0.155**	0.183	0.000	0.591**	0.009**	0.269**

Remark: ** symbol indicates results for significance level 0.05, * for 0.1

4.3. Impulse response function

An analysis of the response to shocks for each variable was conducted. Variable shock is defined as an increase in its value by one standard deviation. It should be emphasized that the order of variables in the vector is significant in the analysis of response to shocks. In the study, the vector consists of the following variables in sequence: inflation, unemployment, WIG20 index, USD/PLN exchange rate, Brent crude oil, and LTI.

The response function to shocks is depicted in Figures 2 and 3. It can be observed that imposing a shock on individual variables leads to immediate responses from the reacting variables. The curves commence from the period *Month* = 1, as the response of variables to the shock of inflation and unemployment is examined in subsequent periods. In most cases, the variable either increases or decreases and then stabilizes at a different level. Special attention was paid to the response of inflation and unemployment to shocks applied to each of the considered variables: inflation rate, unemployment rate, WIG20 index, USD/PLN exchange rate, Brent crude oil index, and ten-year government bond yield. The confidence intervals are limited by red lines.

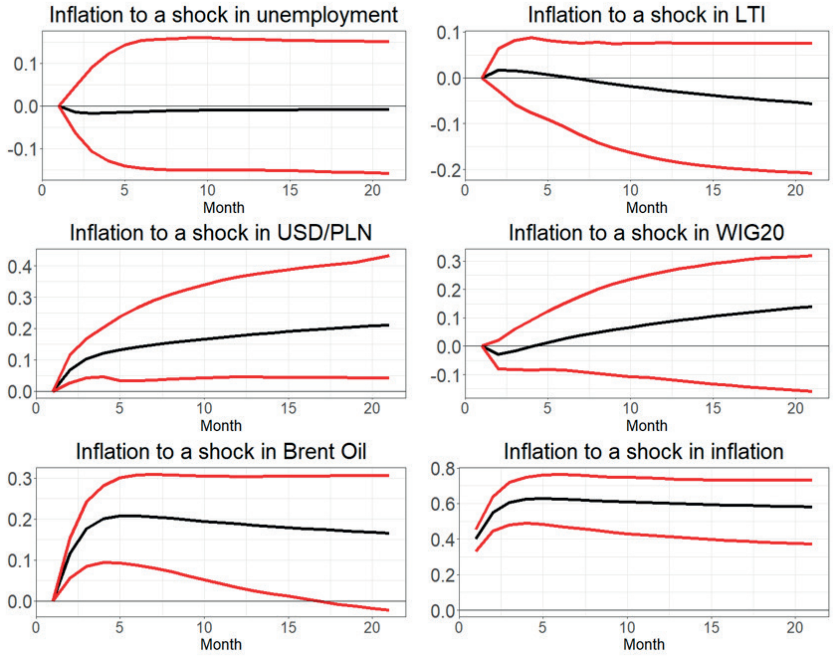

Figure 2. Impulse response function – inflation response

The reaction of the inflation rate to a shock from the unemployment rate, which can be observed in the top left graph of Figure 2, indicates that an increase in the unemployment rate by one standard deviation leads to a slight decrease in unemployment over a quarterly period. This suggests a trade-off between unemployment and inflation in accordance with the Phillips curve theory. In the subsequent months, there is a very slight decrease in unemployment, which stabilizes after a ten-month period. This means that in the observed period, there was a short-term negative relationship between unemployment and inflation in Poland. Milton Friedman already observed short-term trade-offs between inflation and unemployment in the late 1970s. He concluded that the decline in unemployment resulting from expansionary economic policies is short-lived because workers quickly realize that despite a nominal increase in their wages, they are unable to purchase more goods and services due to simultaneous price increases. As a result, some workers quit their jobs, reducing the labor force supply. Unemployment then returns to its natural level, while prices remain at a higher level (Grabia 2016).

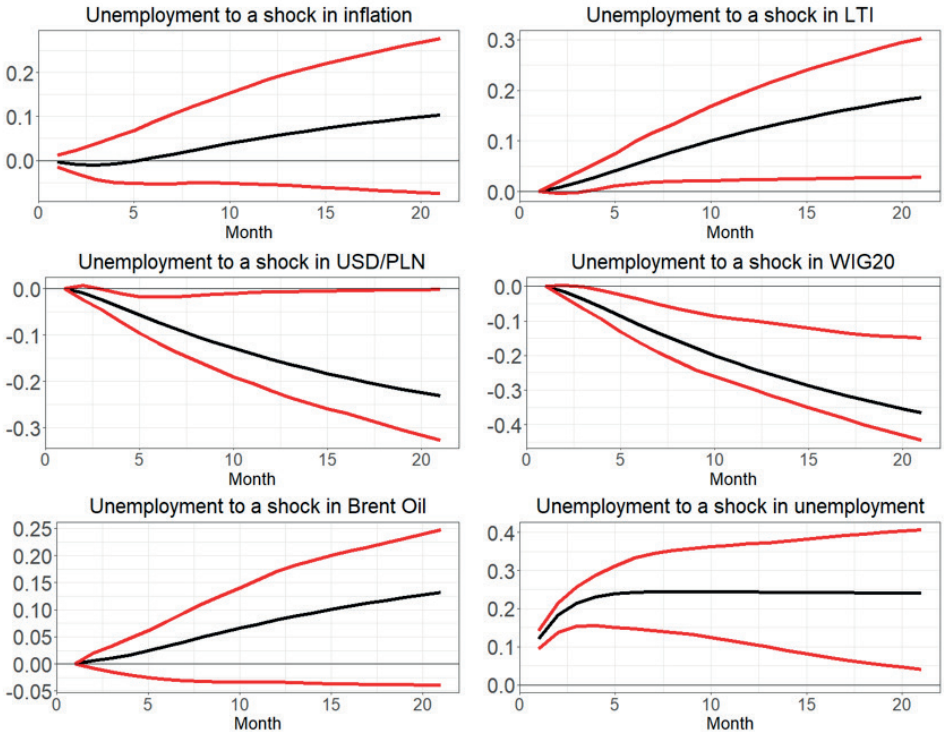

Figure 3. Impulse response function – unemployment response

An increase in the interest rates of 10-year government bonds by one standard deviation results in a slight increase in inflation over the first two months following the shock. In the subsequent months, there is a noticeable decrease in inflation, indicating that raising interest rates by the central bank does not lead to an immediate decrease in inflation. However, it is necessary to explain how the central bank influences long-term government bond interest rates.

Modern monetary policy, whose primary goal is to maintain inflation at the target level, primarily revolves around interest rate policies aimed at stabilizing market interest rates. This stabilization includes, among other things, reducing transaction costs and safeguarding the financial market by minimizing fluctuations in the prices of financial assets. Central bank decisions regarding interest rates have a tangible impact on the economy through the transmission mechanism, which represents the causal relationships between central bank actions and the reactions of economic entities and institutions to a given stimulus. Considering that the effects of implementing a specific monetary policy become evident with some delay, it is crucial for the central bank to make decisions regarding changes in interest rates with appropriate foresight (Przybylska-Kapuścińska 2008).

The graph of the response function of the inflation rate to a shock from the WIG20 index indicates that within one month, a sudden change in its value results in a slight decrease in inflation. Over the long term, an increase in the value of the WIG20 index leads to a continuous increase in the inflation rate. It turns out that high inflation can be a determinant of profit for the stock market. The reasons for this phenomenon appear to be as follows:

- In the case of significant inflation growth, individuals with savings seek higher returns to protect their capital from the devaluation of money to a greater extent than bank deposits.
- Savers typically react to inflationary events with a delay and tend to overestimate their duration.
- The relatively slow pace of interest rate increases by the National Bank of Poland (NBP) in the last two years has led to a significant gap between real interest rates and the inflation rate, further discouraging savers from investing their capital in bank deposits (Przasnyski 2020).

It implies that high inflation, which is a clear sign of weak economic conditions, may not necessarily have a negative impact on stock indices.

As a result of a sudden change in the exchange rate of USD, the inflation rate consistently increases over the studied period. An increase in USD exchange rate means that PLN loses value, leading to inflation and economic slowdown. However, after six months, this growth slows down. The reason for this slowdown

is the impact of restrictive monetary policy instruments such as raising reserve requirements or increasing interest rates.

The influence of an oil shock on the inflation rate in Poland has a similar nature to that observed for the USD exchange rate. In the first five months, there is an increase in inflation, followed by its stabilization. An increase in oil prices leads to increased inflationary pressure, although the intensity of this pressure may vary depending on the level of development of the economy (Geise 2015).

The response of the inflation rate to a shock in itself indicates the presence of a moderate inflationary spiral phenomenon over a period of five months from its occurrence. The inflationary spiral phenomenon involves the occurrence of an inflationary impulse, such as an increase in energy commodity prices or rising import costs, leading to increased production costs and subsequently higher prices. As a result of price increases, workers demand higher nominal wages. If this increase occurs at a faster rate than the growth rate of labor productivity, it leads to an increase in unit labor costs. If businesses do not decide to reduce their profit margins, another round of price increases occurs, considering the increase in employee wages (Belka 1985). The graph shows that the inflationary spiral has a relatively strong but short-lived nature, as inflation stabilizes after five months.

The graph of the unemployment rate's response to an inflationary shock indicates that in the first quarter, the increase in the inflation rate caused a slight decrease in the unemployment rate, confirming earlier observations suggesting a short-term trade-off between unemployment and inflation, as per the Phillips curve theory. Over a longer period of time, there is a simultaneous increase in both the unemployment rate and the inflation rate, leading to the phenomenon of stagflation. This occurs because as price levels rise, the demand for goods decreases, while the quantity of real production supplied to the market increases with rising price levels. Increasing prices lead to a decrease in the real value of money, an increase in loan interest rates, and a reduction in consumer spending. All these factors contribute to a decrease in global demand. Meanwhile, rising prices lead to a decrease in the real wage rate, defined as the ratio of nominal wages to prices. This, in turn, results in increased production levels and employment for profit-maximizing firms. With continued price increases, it becomes impossible to maintain a constant level of real wages in a tight labor market. This means that simultaneous increases in prices and wages prevent further reductions in real wages, and production and employment will no longer respond to price level increases. Employers are then forced to reduce operating costs through workforce reduction (Joint Economic Committee 1980).

The response of the unemployment rate to an increase in long-term bond interest rates indicates that rising interest rates led to a sustained increase in the unemployment rate. As a result of higher interest rates, the costs of servicing loans

increase, reducing demand in the economy, which contributes to a decrease in inflation. A decrease in demand leads to companies reducing production, and the rising interest expenses force them to seek savings through workforce reduction. This suggests the possibility of describing the relationship between unemployment and inflation using the Phillips curve in the short term.

The graph of the unemployment rate's response to a stock market index shock shows a decrease in the unemployment rate in response to the growth of the WIG20 index. The inflation rate increased due to the stock market shock, providing further evidence of the negative relationship between unemployment and inflation in Poland. This is also confirmed by the reactions of the inflation rate to shocks from the USD exchange rate. An increase in the USD exchange rate leads to an increase in inflation while simultaneously reducing unemployment.

Examining the response of unemployment to an oil shock, one can observe its consistency with the response of inflation to a similar stimulus. The difference lies in the strength of the impact of the stimulus, as unemployment does not stabilize over a longer period of time. The constant increase in production and transportation costs forces companies to lay off employees to reduce costs in a situation where demand in the economy is constrained by rising inflation.

The response of the unemployment rate to its shock is similar to the response of the inflation rate to an inflationary shock. In the initial period, weak economic conditions drive a dynamic increase in the unemployment rate, which stabilizes after half a year with changes in macroeconomic policy (Przybylska-Kapuścińska 2008).

4.4. Variance decomposition

Variance decomposition was carried out to identify the variables whose shocks play the most significant role in explaining the variance of individual variables. Figure 4 illustrates the decomposition of each variable over 24 consecutive periods, which corresponds to the next two years. The darkest color corresponds to the inflation variable, and the brightest color represents the LTI variable.

It can be observed that the behavior of all variables is primarily explained by their own shocks, especially in the initial periods. Initially, inflation explains 100% of the variability in its variance, but this influence decreases over time, stabilizing at around 80% after 12 months. Unemployment is primarily explained by unemployment shocks, but this influence quickly diminishes, stabilizing at a level of 40% after 24 months. Over time, the impact of the WIG20 index increases, exceeding 40% after two years. The variance of the WIG20 index is explained by the WIG20 variable in almost 100% throughout all subsequent periods. For the USD/PLN exchange rate, the shock of this rate explains 50% of the variance

initially, gradually waning and stabilizing at 20%. The shock of the WIG20 index has a greater impact, with its influence increasing from 50% to almost 80% after 24 months. Brent crude oil explains 80% of the variance in its own shocks, but this value slowly decreases, while the influence of the WIG20 index rises to approximately 30% after two years. The 10-year government bond interest rate explains 80% of the variance in its own shocks, but this influence rapidly decreases to 40%. Inflation and the USD/PLN exchange rate have a similar impact, accounting for 20% of the variance.

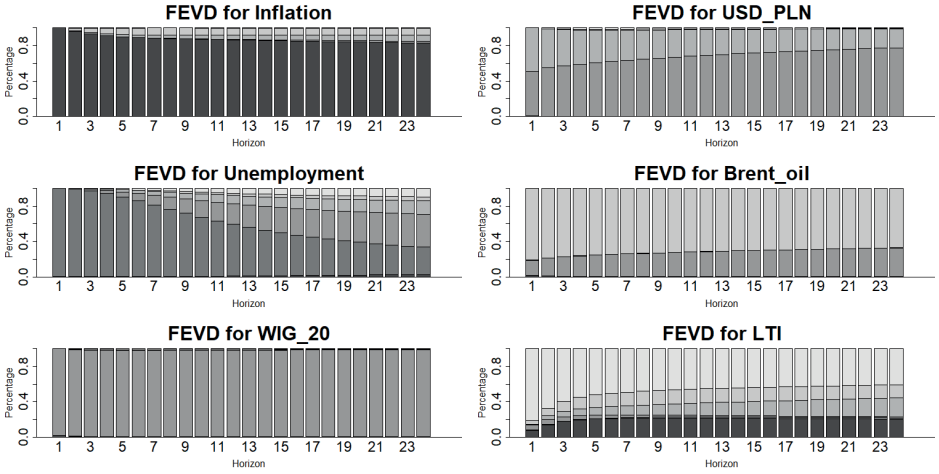

Figure 4. Variance decomposition

5. Conclusion

The study conducted an analysis of the relationship between the inflation rate and the unemployment rate in Poland and their long-term relationships with selected macroeconomic variables: WIG20 index, USD/PLN exchange rate, Brent crude oil prices, and LTI, which represents the interest rate on 10-year government bonds. The analysis was conducted with the use of VECM (Vector Error Correction Model).

The results obtained indicate the existence of one cointegrating relationship among the variables. Variables describing unemployment, inflation, and WIG20 return to the long-term equilibrium state. However, for the remaining variables – USD/PLN exchange rate, Brent crude oil, and LTI – they move away from the long-term equilibrium state in subsequent periods. Analyzing the autoregression

coefficients of the VECM model, it can be observed that in the short term, inflation is significantly influenced by the lagged values of three variables: inflation, exchange rate, and Brent crude oil.

The analysis of impulse response functions provided insights into the response of a given process to a shock in another variable. Special attention was paid to the response of inflation and unemployment to shocks from the variables examined in the study. According to the Phillips curve theory, these variables exhibit a negative correlation in the short term, whereas in the long term, there is a positive relationship leading to the occurrence of stagflation.

The variance decomposition analysis helped identify the variables whose shocks best explain the variability of other variables over time. For inflation and WIG20, these variables respond most strongly to their own shocks. The variability of the inflation rate is explained by an inflation index by more than 80%. Unemployment is strongly influenced by the impulse of the WIG20 index. In the case of the 10-year government bond interest rate, significant influences come from the impulses of inflation and the USD/PLN exchange rate.

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Summary

The purpose of this paper is to examine the relationship between the inflation and unemployment rates in Poland and to analyze their long-term relationships with selected macroeconomic variables: the WIG20 index, consisting of the 20 largest Polish companies noted on Warsaw Stock Exchange, the USD/PLN exchange rate, the Brent crude oil index, and the interest rate on 10-year government bond yields. The main objective of the study is to determine the relationship between inflation and unemployment. In this study, a vector error correction model (VECM) was used to study long-run dependence. The impulse response function and forecast error variance decomposition were also used to examine the interactions between variables. There is one long-run relationship between the factors studied. Both the values of the VECM model parameters and the results of the impulse response function indicate that there is a negative relationship between inflation and unemployment in the short term. In the long term, there is a positive relationship, resulting in the stagflation phenomenon.

JEL codes: C32, C51, E31

Keywords: *VECM, inflation, unemployment, impulse response function, variance decomposition, cointegration*

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Felix Weißensteiner*

Literature review. Pricing rule alternatives for the European day-ahead market

1. Introduction

The day-ahead market occupies a central position within liberalized electricity markets, establishing reference prices for wholesale electricity on an hourly basis for the subsequent day. These reference prices play a crucial role in coordinating all other segments of the electricity market, including over-the-counter (OTC) transactions. Consequently, the prices determined in the day-ahead market exert a significant influence on the profitability of electricity producers and subsequently affect consumer prices, thus affecting the profitability of retail suppliers.

From the end of 2021 throughout the year of 2022, the electricity sector has witnessed a significant rise in consumer prices, attracting considerable attention from both political and media spheres. The escalation of consumer prices in 2022 prompted concerns, which were echoed in notable political speeches, such as that of EU Commission President Ursula von der Leyen, as well as widespread coverage in newspapers. The underlying cause of these high consumer prices was primarily attributed to soaring wholesale prices (Fig. 1), placing the focus on the pricing rule implemented in the wholesale market.

This pricing rule was then often referred to as merit order and simplified as the most expensive generation technology used determines the prices for all producers. In 2022 this meant the enormously increased natural gas prices triggered high wholesale electricity prices for all producers. This, combined with the argument that only 20% of the electricity in the European union is generated from natural gas, (see Fig. 2) was seen as a proof of the inefficiency of the working of this market.

* University of Graz, Austria, e-mail: felix.weissensteiner@uni-graz.at

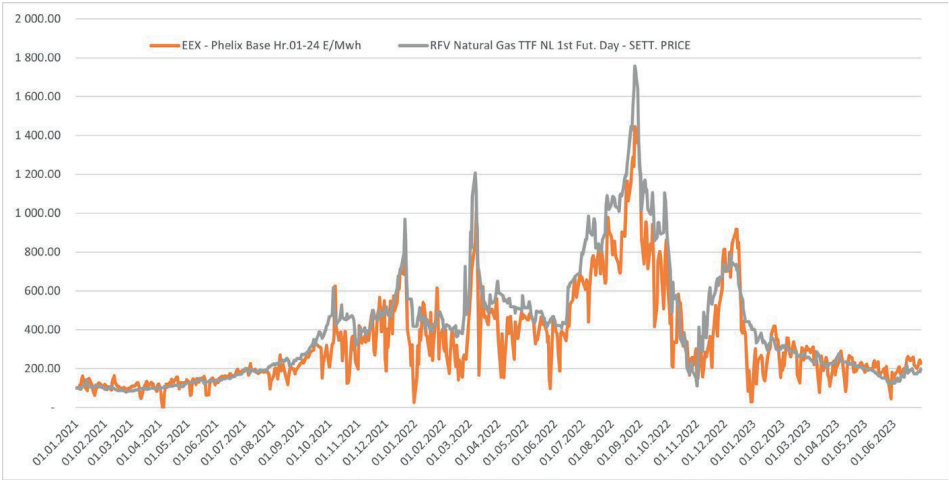

Figure 1. Development of electricity wholesale prices and natural gas prices from 2021 to 2023

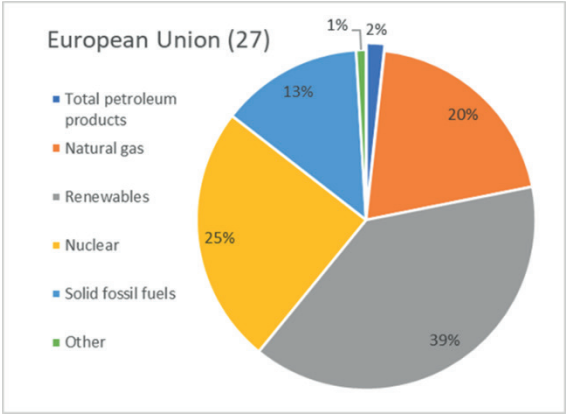

Figure 2. Electricity generation mix for European Union in 2021

Source: Eurostat

Figure 1 illustrates the EEX-Phelix-Base 01-24 in €/MWh, representing the daily average of wholesale electricity prices for the Austria/Germany zone, as well as the Refinitiv Natural Gas Title Transfer Facility Netherlands First Futures Month in €/MWh serving as a reference for the Gas Price. The figure show cases the evolution of these two indices, which have been normalized to a starting value

of 100 in January 2021. The depicted time frame spans from 2021 to April 2023. One can see the enormous rise in both prices for 2022.

Throughout post-liberalization history, a recurring trend emerges: whenever there is a surge in electricity prices, the focus inevitably turns to the pricing rule of the day ahead market.

Notable examples include the summer of 2000 in California, when wholesale electricity prices skyrocketed by nearly 500% compared to previous years. This alarming situation sparked intensive discussions of pricing rules within the main electricity markets, as in P.L. Joskow and E. Kahn (2002) and E. Kahn et al. (2001). Similar scenarios unfolded in Germany, as discussed by V. Grimm et al. (2008) and J. Haucap (2013), as well as in Britain, as discussed by C.D. Wolfram (1999) and N. Fabra et al. (2002).

Furthermore, alongside political concerns regarding the pricing rule's effect on market inefficiencies, academia has extensively explored another critical issue known as the "missing money problem." This refers to the observation that after the liberalization, wholesale electricity prices have been too low to cover the total costs of the electricity producers. The conclusion once again was the wholesale electricity market is working inefficiently, and diminishes incentives for investment, which hinders the investment in renewables as well as possibly leading to future problems concerning the security of supply.

In order to increase the investment in renewable energy generation, schemes for direct governmental support have been introduced. These schemes increased the profitability of renewables but, depending on their structure, reduced the profitability of the other generation technologies (e.g., all baseload technology in Germany, J. Haucap (2013)). To counteract the missing money problem and the increasing share of renewable generation, balancing or capacity markets were introduced to the "energy-only" markets. The structure of a balancing market differs depending on the country, but the principle is largely the same: producers are financially rewarded for providing potentially used capacity. The construction of a balancing market is also an argument for the inefficiency of the working of the wholesale electricity market.

A different perspective emerges when examining the relation between installed capacity and peak demand. It has become apparent that even before the liberalization of electricity markets, many countries had overcapacity, wherein the installed capacity exceeded the peak demand, for example, see S. Moret et al. (2020). This phenomenon has only intensified since market liberalization (Fig. 3). In such circumstances, it is efficient for wholesale prices to not cover total costs, since investment in new capacity shouldn't be profitable. This hampers progress towards achieving climate goals. The introduction of a balancing market, on the other hand, made it profitable even to invest in overcapacity that might never be dispatched.

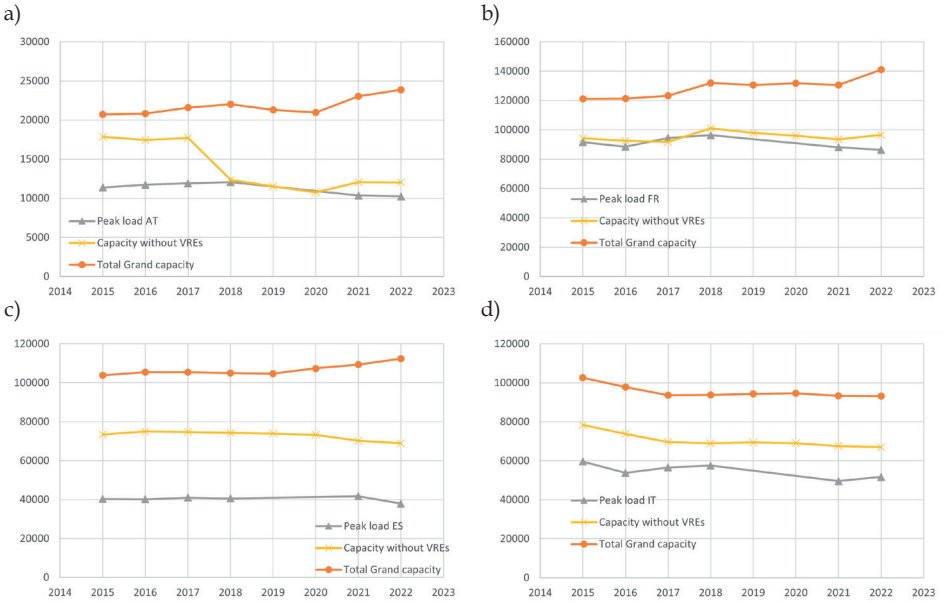

Figure 3. Development of peak load and Installed Capacity: a) peak load, installed capacity and installed capacity without variable renewables in MWh for Austria from 2014 to 2022; b) peak load, installed capacity and installed capacity without variable renewables in MWh for France from 2014 to 2022; c) peak load, installed capacity and installed capacity without variable renewables in MWh for Spain from 2014 to 2023; d) peak load, installed capacity and installed capacity without variable renewables in MWh for Italy from 2014 to 2022

Figure 3 is constructed from ENTSOE data for yearly peak load averaged on the hour and net generating capacity installed in the country. We can see that the orange line, depicting the total installed capacity, overshoots the peak load, depicted in grey, for the time period from 2015 to 2022. This shows the amount of overcapacity present in European countries. Through the balancing market, the costs of this highly inflated market are priced to the consumers.

Furthermore, despite the prevalence of overcapacity, there have been several instances where systems came close to experiencing blackouts or brownouts. The main contributor to this problem is the variable nature of renewable generation. When comparing the installed capacity to peak demand, it is clear that there is costly overcapacity in the system. However, when we exclude renewable sources from the equation (represented by the yellow lines in Figure 3, particularly in cases where a significant share of nuclear power plants, such as in France, is currently maintained, we can observe that peak demand reaches the capacity limits.

The intricate nature of the electricity wholesale market, compounded by constant political intervention, complicates the assessment of its working. These interventions often erode investment incentives (apart from renewables) and always increase (political) risks. While the translation of wholesale prices to consumer/retail prices falls outside the scope of this paper, the findings of the Austrian Bundeswettbewerbsbehörde in their investigations published in July of 2023 are worth noting: they indicate that there is limited competition within the retail supplier market. Consequently, rising wholesale prices tend to translate into rising consumer prices, while decreases in wholesale prices only gradually translate to lower prices for end consumers.

In light of these complexities and their far-reaching implications, a comprehensive analysis of pricing rules in the day-ahead market becomes imperative. This paper aims to contribute to the understanding of the market's efficiency, laying the groundwork for informed discussions on potential improvements and policy interventions. By doing so, we aspire to promote a more sustainable and economically viable electricity market that supports the transition to renewable energy sources while ensuring reliable and affordable electricity for consumers.

Considering the complexities and challenges faced by the electricity market, this paper aims to provide a comprehensive review of the academic literature concerning different pricing rules for the day-ahead market. The primary research questions that motivate this literature review are as follows:

1. What criteria are used to evaluate pricing rules for the day-ahead market in variousstudies and how can they help to improve the current discussion?
2. What alternative pricing rules exist for the day-ahead market, and how do they perform according to the identified criteria for evaluation?

By conducting a thorough review of the academic literature, this paper intends to contribute to the understanding of the implementations of pricing rules in the day-ahead market. Rather than focusing solely on short-run prices, this analysis considers broader perspectives such as investment incentives, security of supply, market structure, and the unique characteristics of electricity as a commodity.

This literature review aims to identify the criteria used to evaluate pricing rules and their performance in the context of the European electricity market. By examining the strengths and weaknesses of different pricing rule alternatives, valuable insights can be gained regarding their suitability for addressing the challenges faced by the market.

It is worth noting that this paper does not delve into broader structural changes or macroeconomic events but specifically concentrates on the analysis of pricing rules in the day-ahead auction. By narrowing the scope in this way, we can provide a focused and in-depth examination of the subject matter.

The rest of this paper is organized as follows. Section 2 provides an overview of the electricity market, including its liberalization, market structure, and its most important market, the day-ahead market. This section finishes by introducing the criteria for evaluating pricing rules.

Section 3 delves into the currently implemented uniform pricing rule (UP) and explores its main competitor, the discriminatory pricing rule (DP), along with the Vickrey–Clarke–Groves pricing rule (VCG), which has garnered academic interest. A comparative analysis of these pricing rules sheds light on their advantages and limitations.

Lastly, Section 4 presents a synthesis of the prominent conclusions drawn from the reviewed literature. It summarizes the key insights and findings regarding the evaluation of pricing rules for the day-ahead market, providing a comprehensive understanding of the subject matter.

In conclusion, this paper aims to contribute to the ongoing discussion and debate surrounding the reform of pricing rules in the European electricity market's day-ahead auction. By critically analyzing the academic literature and examining different pricing rule alternatives, this research strives to enhance our understanding of the factors that should be considered when designing efficient and effective pricing mechanisms.

2. The European day-ahead market

2.1. Liberalization of the European electricity market

The electricity market encompasses four primary components: generation, transmission, distribution, and consumption.

Electricity generation is a complex and dynamic process that involves a multitude of technologies, inputs, and operational considerations. Each technology presents its own set of advantages, limitations, and environmental implications. Operational limits, such as temperature thresholds and load balancing, are crucial to prevent damage to the equipment and to ensure the stability of the power grid. Additionally, the supply of electricity is subject to uncertainties arising from weather conditions, seasonal variations, and the need to effectively match the unpredictable patterns of consumer demand.

Transmission, as a critical component of the electricity system, involves the long-distance transfer of power. However, it faces inherent limitations dictated by fundamental physical laws, most notably Kirchhoff's Laws, which impose restrictions on the capacity of transmission lines. These limitations arise from factors such as line losses, voltage drop, and thermal constraints, necessitating careful management and planning of the transmission infrastructure.

Distribution encompasses the local transfer of electricity over shorter distances, typically from distribution substations to end consumers. This stage of the electricity supply chain involves transforming the high voltage electricity from transmission lines into lower voltages suitable for consumption by households, businesses, and other entities. Effective coordination and synchronization between transmission and distribution networks are crucial to ensure the efficient and reliable delivery of electricity to end-users. Even though they have a major influence on the efficient working on the liberalized market as well as the implementation of the optimal pricing rule, we will basically exclude them from the scope of this paper.

The inelastic nature of electricity demand, where consumers' electricity consumption remains relatively unchanged despite price fluctuations, has significant implications for market clearing. This lack of responsiveness to price changes, attributed in part to prevalent consumer contracts that insulate consumers from short-term price variations, can lead to imbalances between the supplied and demanded quantities at a given price level. However, the introduction of smart meters and their increasing rollout holds promise for addressing this problem. Smart meters provide real-time information on electricity use and pricing, enabling more dynamic pricing structures and empowering consumers to make informed decisions about their energy consumption.

In the past, the electricity market was operated by vertically integrated monopolies, as depicted in Figure 4. These monopolies controlled all aspects of the market, and prices were set by pricing committees based on costs and a stable return.

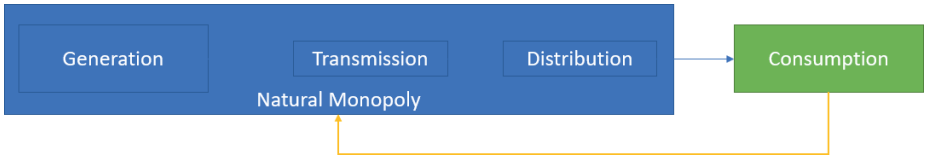

Figure 4. Monopolistic electricity market before liberalization

As a result of liberalization, a fundamental reorganization took place, leading to the dismantling of long-standing monopolies and the introduction of competition in both the retail supply and the generation of the electricity (Fig. 5). The motivations driving this liberalization, as highlighted by F.P. Sioshansi (2006), were multifaceted and encompassed objectives such as eliminating inefficiencies, addressing regulatory complexities, overcoming inadequate investment in infrastructure, and facilitating decentralized decision making. The overarching

goal was to establish a regulated, non-discriminatory, and transparent electricity market accessible to all participants, as emphasized by N. van Bracht et al. (2019). This restructured and liberalized electricity market aims to foster competition, promote efficiency, and enhance overall market dynamics for the benefit of consumers and the industry as a whole.

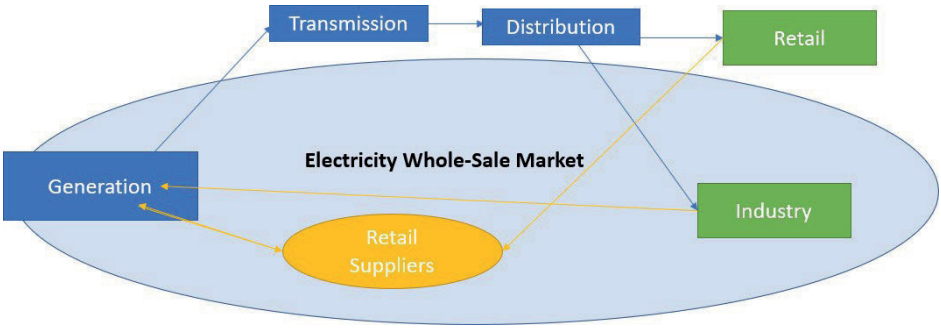

Figure 5. The Liberalized Electricity Market

The wholesale market stood as the cornerstone of the newly established electricity market, facilitating competitive generation and supply. It was believed that fostering competition between multiple producers would lead to a more effective reduction of wholesale prices compared to price regulation in a non-competitive market. However, this competitive market structure presented challenges in terms of ensuring fair and transparent electricity pricing.

In addition, the transmission and distribution of electricity were excluded from competition due to the potential negative effects that could arise from an unregulated approach. Consequently, investment in transmission networks remain highly regulated, ensuring the reliability and stability of the grid, while investment in generation capacity is now open to participation from various market players. This differentiation in competition has helped strike a balance between promoting efficiency and maintaining the necessary control and oversight of critical infrastructure components.

To address the challenges experienced in regions such as Italy and California, where blackouts and capacity-related problems emerged, ancillary markets were established. While transmission and distribution remained under regulated frameworks, ancillary markets played a crucial role in managing the challenges associated with supply–demand imbalances and congestion. Through their establishment, liberalized electricity systems aim to enhance the resilience, responsiveness,

and overall reliability of the grid, drawing lessons from past experiences to build a more robust energy infrastructure.

Several papers, such as T. Jamasb and M. Pollitt (2005), have investigated the effectiveness of the liberalization at achieving the advocated goals. It was found that the level of competition is still relatively low in all liberalized segments, including generation and retail supply. This can be attributed to the inherent characteristics of the electricity market, such as the presence of economies of scale, oligopolistic ownership, entry barriers, inelastic and volatile demand, and strategic bidding. These factors make the market susceptible to market power abuse, leading to distorted prices and inefficient outcomes. Therefore, the design of pricing rules and auction mechanisms becomes crucial in promoting competition, mitigating market power, and achieving efficient market outcomes.

The level of competition is especially low in the retail supplier segment, which also explains why rising prices rapidly translate into consumer prices but lowering prices do not. For instance, the Bundeswettbewerbsbehörde in Austria has published a graphic illustrating the Herfindhal–Hirschman Index (HHI) for different regions, highlighting the considerable market concentration (Fig. 6).

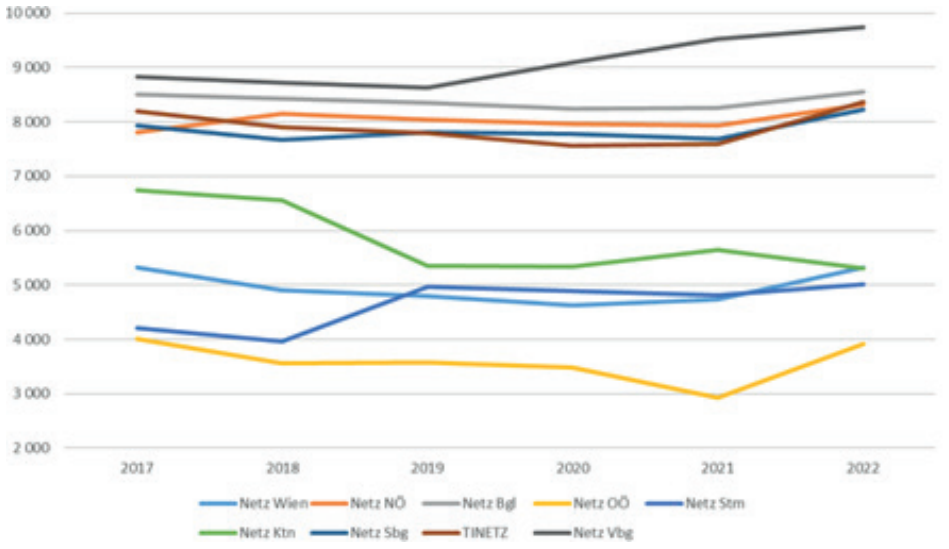

Figure 6. Development of HHI of the retail supply for Austria's nine regions

Similar findings have been observed in other European countries as well.

Furthermore, the transition from state ownership to private ownership of electricity generating companies has not occurred as extensively as expected.

This is evident in the ownership structure graphic (Fig. 7) of electricity generating companies in Austria, where dark green boxes represent entities that are 100% state owned. It is apparent that the state continues to play a significant role in electricity generation. It is worth noting that Austria is not an isolated case, as this pattern is also observed in other countries across Europe. This example was chosen due to the recent publication of the E-Control investigation.

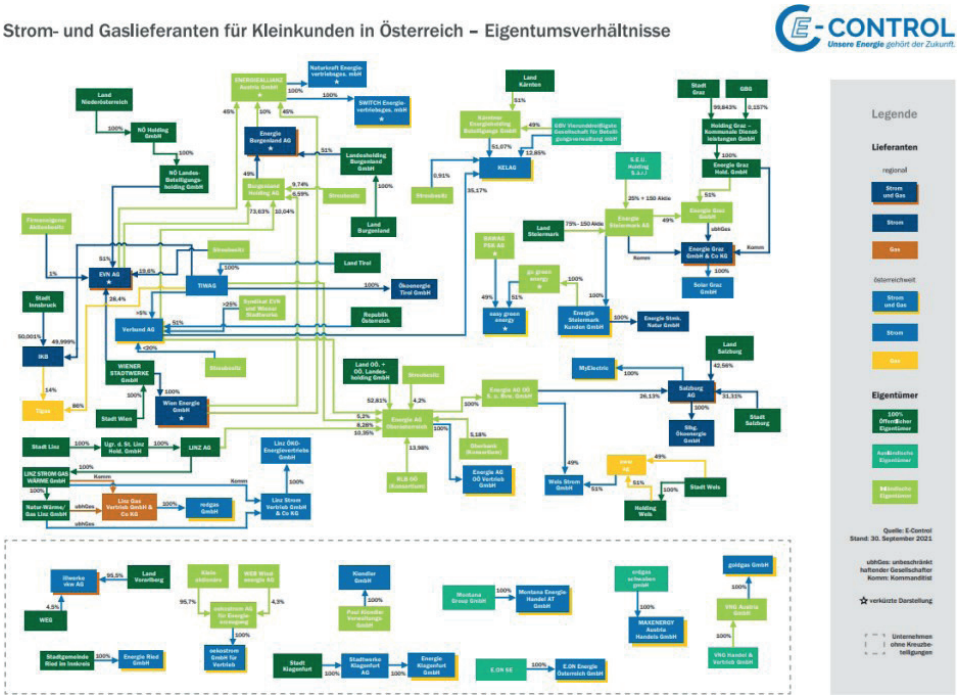

Figure 7. Ownership structure of electricity generating companies in Austria

2.2. The wholesale electricity market

The wholesale market for electricity comprises spot markets, which include the day-ahead and intraday markets, as well as long-term markets, which include futures, forwards, and options.

Among the spot markets, the day-ahead market holds significant importance, as already mentioned. Operated through power exchanges, it serves as the central market for electricity. Participants in the day-ahead market optimize their portfolios by submitting bids for the following day. This allows, for example,

producers to efficiently manage their electricity supply in response to anticipated demand. The day-ahead market's influence, due to arbitrage, extends beyond the spot markets and affects the pricing in all other markets, including OTC trades.

Bidding rules govern the day-ahead market auctions: market participants submit bids specifying the quantity of electricity (in megawatt-hours) and the price (in euros per megawatthour) for each hour of the following day, while adhering to price floors and caps set by the rules of the market. To accommodate the increasing complexity of the generation of electricity, including the inclusion of renewable energy sources, the introduction of complex bids and block bids have become essential. Complex bids allow participants to express more sophisticated pricing strategies, while block bids enable the submission of bids for consecutive hours or even an entire day. Additionally, step-wise bid functions provide participants with the flexibility of specifying different prices and quantities for various price levels, or "steps." This can allow more nuanced price differentiation and better reflect the cost structures or market strategies of the different producers. However, it is important to recognize that an increased number of steps as well as all other bid amendments can also raise the risk of strategic bidding, where participants manipulate their bids across different price levels to influence market outcomes and maximize their own profits. Effective monitoring and regulation are crucial for mitigating the potential for strategic behavior and ensure a fair and competitive market environment.

Clearing rules determine the outcome of the day-ahead market auctions. Aggregate supply and demand curves are formed based on the submitted bids, representing the quantities of electricity supplied and demanded at different price levels. The market clearing price (MCP) is determined by the intersection of these curves, indicating the price at which the supply and demand of electricity are balanced. Individual market participants are then allocated quantities of electricity based on the clearing price and their submitted bids.

To provide a visual representation of the market clearing process, Figure 8 shows the aggregate supply and demand curves for a hypothetical hour in the day-ahead market. The supply curve depicts the relation between the quantities of electricity supplied and the corresponding prices, starting with lower quantities for low prices and gradually increasing as prices rise. On the other hand, the demand curve depicts the quantities of electricity demanded at different price levels, exhibiting a relation that is inverse to that of the supply curve. The MCP is determined by the point of intersection between these curves, indicating the price at which the supply and demand of electricity are in balance. The MCP plays a crucial role in influencing the prices that participants either receive or pay for the electricity they trade in the market, reflecting the equilibrium between the quantity supplied and the quantity demanded.

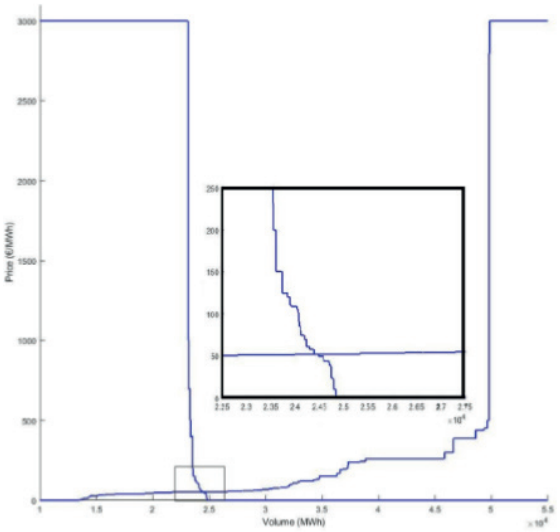

Figure 8. Clearing rule in DAM

Source: Soloviova et al. (2021)

2.3. Criteria for evaluating pricing rules

After the MCP is determined, the pricing rule decides what prices the winning bidders pay and receive as well as what happens with differences between the two sums. The evaluation of pricing rules in the day-ahead market encompasses multiple perspectives, including efficiency-theoretic ones and the political point of view.

From an efficiency-theoretic perspective rooted in economic theory and mechanism design, a pricing rule should aim for **productive efficiency**, which maximizes the efficiency of the current generation portfolio. In electricity markets, productive efficiency is synonymous with an efficient dispatch, where generators are dispatched in order of the lowest marginal cost. To achieve this, it is crucial that the producers' bids reflect their costs, a concept known as **truthful bidding**. If the pricing rule encourages truthful bidding as a dominant strategy, an efficient dispatch is guaranteed. Moreover, promoting truthful bidding simplifies the process of deciding on a bid, enhancing efficiency and fostering participation from smaller bidders (Lange et al. 2022).

On the other hand, the political perspective focuses on what is perceived as beneficial for consumers and aligns with political agendas. This perspective often prioritizes **low average prices** to ensure affordability for consumers and

supports sustainability goals, particularly by incentivizing investment in renewable energy sources. However, it is important to strike a balance, as excessive profits for producers can generate high political costs due to public perceptions of unfairness. Therefore, discussions surrounding pricing rules often emphasize the need to ensure reasonable profits for producers while preventing excessive profits that might generate public backlash. This consideration shapes the evaluation of pricing rules and influences discussions surrounding incentives for investment and the fairness of the market.

In evaluating pricing rules, the **consumer surplus** is often included as a metric. Consumer surplus measures the difference between the willingness to pay for a unit of electricity and the charged price. Maximizing consumer surplus entails setting prices equal to the marginal costs for each unit of electricity. However, this approach may not cover the producers' fixed and total costs, affecting their profitability and incentives for long-term investment. The profitability and price stability of producers play a critical role in shaping their incentives for investment, which, in turn, shape the future generation portfolio. Negative profits can deter investment in generation capacity, which may be efficient in the case of overcapacity but problematic under normal capacity conditions. Positive investment incentives are currently politically motivated by the pursuit of climate goals.

Another important criterion for evaluating pricing rules is their effect on preventing **predatory, entry-deterring, and collusive behavior**. These behaviors interact with the aforementioned metrics in various ways, with truthful bidding being a key consideration. Truthful bidding becomes achievable when market power is minimal, as it influences the asymmetry of profits between producers of different sizes and the costs associated with market entry. Collusion directly affects short-run efficiency by driving prices above the level achievable under perfect competition, while entry-deterring behavior reduces competition and leads to long-run inefficiency. Predatory behavior can take different forms, such as supply reduction. Therefore, an ideal pricing rule should foster a level playing field, discouraging collusion and predatory pricing, while promoting fair competition and encouraging market entry.

Simplicity of pricing rules is also valued, as this ensures rational behavior by bidders and facilitates the correct interpretation of the results of the market.

In summary, the evaluation of pricing rules in the day-ahead market involves balancing the efficiency theoretic and political perspectives. It encompasses criteria such as productive efficiency, consumer surplus, investment incentives, prevention of anti-competitive behavior, simplicity, and market fairness. Striking the right balance is crucial to develop pricing rules that achieve both political objectives and market efficiency while ensuring fair outcomes for all stakeholders.

3. Literature review

The objective of this literature review is to analyze and characterize pricing rules in electricity day-ahead markets. By examining the academic literature, we aim to gain insights into the various approaches and assumptions adopted in studying pricing rules in these markets. This review seeks to provide a comprehensive understanding of the structure of the supply, the characteristics of the demand, information certainty, and other important factors that influence the performance of a pricing rule. Through this analysis, we aim to shed light on the effectiveness and limitations of different pricing rule frameworks and contribute to a broader understanding of the dynamics of an electricity day-ahead market. The literature can be categorized into four main approaches: analytical, theoretical, empirical analysis, and simulation studies. This review aims to provide an overview of the different approaches and their assumptions.

Analytical papers

Analytical papers form the majority of the literature an overview of of the reviewed analytical papers is given in Table 1. Analytical papers are characterized by precise assumptions and mathematical derivations of their results. These papers primarily focus on the supply structure, characteristics of the demand, and information certainty. While assumptions regarding the supply structure are essential for analytical modeling, it is worth noting that the assumption of an asymmetric oligopoly, which closely reflects the reality (Grimm et al. 2008; Vasin 2014), is relatively scarce in these papers due to its complexity. However, alternative assumptions regarding the structure of the market are sometimes considered to explore different scenarios and assess the potential impacts on outcomes. For instance, alternative models may model perfect collusion through a monopolistic market setup.

Regarding demand assumptions, a certain demand is often assumed for markets with "shortlived" bids, such as hourly segments of the day-ahead market, due to the high persistence of demand (Fabra et al. 2002, 2011). Additionally, assuming inelastic demand in the short run is reasonable since the retail consumption share is unable to respond to price changes, which are likely to affect the day-ahead market (see 2.1). However, an assumption of more elastic demand is also plausible in the long run, considering the deployment of smart meters and the adaption of behavior or contracts.

Another crucial assumption relates to the degree of certainty of the information that suppliers have regarding their cost structures and those of their competitors. This assumption plays a significant role in analytical modeling and influences the strategic decision-making of market participants.

Analytical papers typically analyze the day-ahead market as a one-shot auction using game theory to determine equilibria. However, a significant limitation arises from the repetitive nature of day-ahead auctions and the potential for strategic learning. To address this limitation, more recent studies have employed evolutionary game theoretic models to capture strategic learning, albeit at the expense of formulating a longer and more rigorous set of assumptions.

Simulation papers

Simulations have gained prominence in the literature due to their ability to capture the dynamics of repetitive and competitive markets, which analytical models may struggle to represent effectively. Simulation studies often adopt a Q-learning agent-based approach, enabling producers to learn and adapt their bidding strategies based on past experiences (Sugianto, Liao 2014). This approach facilitates the exploration of the effects of repeated trading in auction markets and provides valuable insights into market behavior and outcomes.

Table 1

Overview of the analytical studies

Author	Year	Approach	DP	UP	VCG	Supply	Symmetric	Demand certainty	Elastic	Cost certainty
Zhao et al.	2023	analytical, empirical	x	x		oligopoly	y	y	n	y
Willems, Yu	2022	analytical	x	x		oligopoly	y	n	y	y
Lange et al.	2022	analytical	x	x	x	oligopoly	y/n	y	n	n
Cheng et al.	2022	analytical	x	x		oligopoly	y	n	y	y
Sessa et al.	2017	analytical, empirical	x		x	oligopoly	n	y	y/n	y
Holmberg, Wolak	2015	analytical	x	x		duopoly	y	n	n	n
Ausubel et al.	2014	analytical	x	x		oligopoly	y	y	both	n

Table 1 cont.

Author	Year	Approach	DP	UP	VCG	Supply	Sym-metric	De-mand cer-tainty	Elas-tic	Cost cer-tainty
Vasin	2014	analytical	x	x	x	oligo-poly	n	y	n	n
Fabra et al.	2011	analytical	x	x		duo-poly	y	y/n	n	y
Holm-berg	2009	analytical		x		oligo-poly	y	n	n	y
Dech-enaux, Ko-venock	2007	analytical	x	x		oligo-poly	y	y	n	y
Fabra	2003	analytical	x	x		duo-poly	y	y	y	y
Fabra et al.	2002	analytical	x		x	duo-poly	y	y	n	y
Fed-erico et al.	2003	analytical	x	x		mono-poly, perfect compe-tition	y/n	y	n	y
Klem-perer, Mayer	1989	analytical	x	x		oligo-poly	y	n	n	y

Theoretical papers

Theoretical papers in this domain serve as summaries of results derived from other academic papers, enriched by concluding remarks. They are particularly prevalent during periods of intensive discussion regarding auction rules and market prices.

Empirical papers

Empirical studies in this area are relatively scarce due to the inherent complexity of isolating the effects of pricing rules within the broader dynamics of the electricity day-ahead market. These studies face challenges in disentangling the specific effects of pricing rules from those of other market factors and external influences.

In summary, the reviewed academic literature on pricing rules in electricity day-ahead markets encompasses analytical, theoretical, simulation, and empirical studies. Analytical papers, while often requiring assumptions on the supply structure, rarely employ the assumption of an asymmetric oligopoly, due to its complexity. Simulation studies have emerged to capture the repetitive nature of day-ahead auctions and facilitate strategic learning. Theoretical papers provide synthesized insights from the existing literature, while empirical studies face challenges in isolating the effects of a pricing rule. Table 2 provides an overview of the analyzed papers, categorized by their approach.

Table 2

Overview of the discussed literature

Author	Year	Approach	Author	Year	Approach
Zhao et al.	2023	analytical, empirical	Dechenaux, Kovenock	2007	analytical
Willems	2022	analytical	Hailu, Thoyer	2007	simulation
Lange et al.	2022	analytical	Fabra	2003	analytical
Cheng et al.	2022	analytical	Fabra et al.	2002	analytical
Heim, Götz	2021	empirical	Federico, Rahman	2003	analytical
Viehmann et al.	2021	simulation	Evans, Green	2003	empirical
Ocker et al.	2018	empirical	Newbery	2003	theoretical
Ocker et al.	2018	analytical, empirical	Rassenti et al.	2003	experimental
Aliabadi et al.	2017	simulation	Engelmann, Grimm	2009	experimental
Sessa et al.	2017	analytial, empirical	Klemperer	2002	theoretical
Holmberg, Wolak	2015	analytical	Joskow, Kahn	2002	empirical, simulation
Ausubel et al.	2014	analytical	Bower	2002	empirical
Sugianto, Liao	2014	simulation	Kahn et al.	2001	theoretical
Vasin	2014	analytical	Wolak, Patrick	2001	theoretical
Haucap	2013	theoretical, empirical	Kagel, Levin	2001	experimental

Table 2 cont.

Author	Year	Approach	Author	Year	Approach
Fabra et al.	2011	analytical	Bower, Bunn	2001	simulation
Azadeh et al.	2010	simulation	Harbord, McCoy	2000	theoretical
Holmberg	2009	analytical	Hudson	2000	simulation
Grimm et al.	2008	theoretical	Wolfram	1999	theoretical
Tierney et al.	2008	theoretical	Fehr von der, Harbord	1998	theoretical
Cramton, Stoft	2007	theoretical	Tenorio	1997	theoretical
Ockenfels	2007	theoretical	Klemperer, Mayer	1989	analytical

Search strategy. The search strategy employed to identify the academic literature to be reviewed was designed to ensure a comprehensive and systematic approach. The initial step involved conducting a keyword search using the terms "merit order" and "pricing rule" in the Scopus database. These keywords were selected to target relevant studies that specifically address the determination of pricing rules in electricity day-ahead markets. The search was limited to the academic literature to ensure the inclusion of rigorous and scholarly works. The identified papers underwent further screening and selection based on their relevance to the research topic and the criteria outlined for the literature review. This search strategy aimed at encompassing a broad range of studies while maintaining a focus on high-quality research in the field of electricity day-ahead market pricing rules.

The next section is organized as follows. Firstly, we will delve into an analysis of the two prevailing pricing rules commonly employed and studied in multi-unit auctions, namely, UP and DP.

We will begin with the examination of the uniform pricing rule, considering it the status quo, and explore its operational characteristics based on the findings from the reviewed academic literature. First we will cover the key features that can be derived from studying the pricing rule independently, without specific assumptions. Subsequently, we will present the characteristics of the uniform pricing rule as concluded by analytical papers, employing different sets of assumptions. Furthermore, we will shed light on the insights obtained from empirical and simulation analyses.

Subsequently, we will follow the same approach for the discriminatory pricing rule. We will examine its workings and characteristics by considering

the theoretical, analytical, empirical, and simulation results. This comprehensive evaluation will allow a direct comparison between the two pricing rules.

Lastly, we will focus on the investigation of the Vickrey auction pricing rule. Although research specific to this pricing rule in the electricity market, particularly the day-ahead market, is relatively scarce, we will include an examination of its general operation. Additionally, we will provide a direct comparison of the Vickrey rule with the other pricing rules. By incorporating these analyses, we aim at offering a comprehensive understanding of the characteristics and implications of each pricing rule in the context of electricity day-ahead markets.

3.1. Alternatives for a pricing rule

3.1.1. Uniform pricing

UP, the predominant pricing rule implemented in European day-ahead markets, operates by ensuring that all winners in the auction receive the MCP, regardless of their bids. Under this pricing rule, all winning buyers value the commodity at or above the price, while all winning sellers value it below the price. This mechanism guarantees that no participant is left with the feeling of "overpaying" or "underpaid" since all participants receive the same price.

However, recent events have highlighted the high political cost associated with UP, making it difficult to justify bidders with very different cost structures receiving an identical price. Despite this challenge, UP continues to be widely used due to its other advantages, which are worth considering.

One of the key advantages of UP is its transparency and straightforward price discovery mechanism. This pricing rule provides clear and unambiguous information about the market price, enabling market participants to easily assess the value of the commodity based on the MCP. Furthermore, UP supports efficient coordination, particularly for OTC contracts. By relying on the UP rule's reference prices as a consistent benchmark, participants can enhance coordination and reduce complexities in contract negotiations. The simplicity of UP is another notable advantage. The absence of complex pricing mechanisms or differentiated payments based on individual bids reduces barriers to entry, encourages market participation, and fosters competition.

Overall, UP's transparency, facilitation of price discovery, coordination advantages for OTC contracts, and simplicity contribute to efficient market operations and reduced transaction costs. These benefits have led to its widespread adoption in most European day-ahead markets, making it the pricing rule of choice for market organizers and participants. However, it's important to acknowledge the challenges associated with justifying UP in situations where bidders have

significantly different cost structures. In order words, the UP rule is equipped with high political costs.

Analytical studies have provided valuable insights into the implications of UP in electricity day-ahead markets. The following points summarize the key findings of these studies.

Perfect competition

Under conditions of perfect competition, analytical studies have shown that UP enables truthful bidding and therefore an efficient dispatch. Studies by G. Federico and D. Rahman (2003) and B. Willems and Y. Yu (2022) have demonstrated that UP in a perfectly competitive setting establishes truthful bidding and leads to an efficient dispatch. It ensures that production is allocated to producers with the lowest costs, promoting efficiency and maximizing social welfare (Cramton, Stoft 2007).

Imperfect Competition

In scenarios of imperfect competition, the following characteristics of UP have been identified:

- Vulnerability to collusion. Uniform pricing has been found to be susceptible to collusion. P.D. Klemperer (2002) and other studies have highlighted the potential for collusive behavior among market participants. Under the UP rule, the bids for marginal units have an influence on the payments for inframarginal units. This creates incentives for punishing deviating producers (Fabra 2003) and signaling between producers (Klemperer, Meyer 1989).
- Supply reduction and bid shading. Analytical studies, including A. Ockenfels (2007), L.M. Ausubel et al. (2014) and J.H. Kagel and D. Levin (2001), have shown that UP can lead to a reduction of the supply and bid shading in imperfectly competitive markets. Generators strategically withholding bids or shading their bids can manipulate the market and increase the MCP, resulting in inefficient dispatch, reduced productive efficiency, and higher consumer prices. With a high degree of market power, a reduction in the supply and bid shading can be exploited through one dominant supplier.
- Factors Influencing Collusive Behavior. Studies by V. Grimm et al. (2008) suggest that uncertain demand and supply, as well as asymmetric characteristics of the producers, can decrease the likelihood of collusive behavior under UP. Greater transparency in market operations, as emphasized by A.E. Kahn et al. (2001), can act as a deterrent to collusion and promote competitive outcomes.
- P. Cramton and S. Stoft (2007) show that UP with an increasing number of competitors converges quickly to complete efficiency.

Monopoly

In a monopolistic setting, UP exhibits the following characteristics.

Monopolistic Pricing. Uniform pricing can be seen as a form of third-degree price discrimination in a monopolistic environment. Analytical studies, such as G. Federico and D. Rahman (2003), have shown that UP allows the monopolist to increase monopolistic profit and capture consumer surplus. Each demand realization can be treated as a separate market, enabling the monopolist to adjust prices accordingly.

Empirical results

Empirical studies have provided evidence of collusive behavior and its impact on creating price spikes. For the UK electricity generation market, P.D. Klemperer (2002), N.H. von der Fehr and D. Harbord (1998), C.D. Wolfram (1999) and F.A. Wolak and R.H. Patrick (2001) highlight instances of collusive behavior leading to price spikes. P.L. Joskow and E. Kahn (2002) found abusive capacity withholding in their analysis of the California market in 2000 when comparing it to an adapted perfect competition base case. Moreover, F. Ocker et al. (2018) demonstrates collusive behavior triggered by the regular repetition and the small and stable set of suppliers in the German balance market operating under UP. Similar conclusions were reached by S. Heim and G. Götz (2021).

Simulation results

Simulations also provide insights into the tendency for strategic bidding under UP. J. Viehmann et al. (2021) present an agent-based simulation demonstrating that UP motivates strategic bidding, particularly through rising prices of second bids. Additionally, A. Hailu and S. Thoyer (2010) and L. Sugianto and K. Liao (2014) confirm the sensitivity of the UP rule to asymmetries of the generators. L. Sugianto and K. Liao (2014) observe a jump in average prices and total dispatch costs, while A. Hailu and S. Thoyer (2010) note bid shading among high levels of competition and large capacity bidders.

Impact of renewable generators

Analytical and empirical studies have highlighted the "merit-order effect" of renewable generators under UP. J. Haucap (2013) analyzes the German market, where prioritized renewable dispatch is implemented within the UP day-ahead market. This implementation shifts the aggregate supply curve to the right, resulting in a decrease in the MCP within the UP setting. As a consequence, revenues for generators are diminished, and the dispatched hours for non-renewable generators decrease, further affecting their ability to recover total costs. Therefore, UP may require higher price spikes to stimulate future investment in new generating capacity.

3.1.2. Discriminatory pricing

A superficial understanding of electricity auctions might suggest that if not all bidders receive the MCP but instead their bid, the overall price paid would decrease. This alternative to the UP rule is commonly referred to as the discriminatory pricing rule (DP) or the pay-as-bid (PAB) rule. The DP establishes for every hour and every producer or bidder a price, thereby eliminating a general reference price.

In March 2001, the British regulatory authority Ofgem initiated a transition from UP to DP in England and Wales. This transition was motivated by the expected reduction in wholesale prices of electricity and the belief that DP is less susceptible to strategic manipulation by large traders. Similarly, before its collapse, the California Power Exchange commissioned a report by leading auction theorists to explore the feasibility of switching to a DP format for the exchange's day-ahead market. This move was prompted by the increasing occurrence of price spikes during both on- and off-peak periods.

Implementing DP in double-sided blind auctions requires certain adaptations, such as specifying how prices are paid to selected suppliers and by selected demands. In the UK, an open auction was implemented to address this, as stated in P. Cramton and S. Stoft (2007). However, it can still be implemented as a non-synchronous auction with reduced transaction costs.

Analytical studies

Analytical studies indicate that even under perfect competition, generators (except for those that only produce when full demand is reached) include a markup in their bids, leading to reduced productive efficiency, consumer surplus, and social welfare (Federico, Rahman 2003; Grimm et al. 2008).

From a game-theoretic perspective, the PAB auction design triggers a "guessing the MCP" game, where participants bid the estimated MCP. Consequently, truthful bidding is not a dominant strategy according to V. Grimm et al. (2008). The absence of truthful bidding results in inefficient dispatch and reduced production efficiency. This "guessing the MCP" game becomes particularly burdensome for small generators. As day-ahead auctions are repeated, participants' estimations of the MCP converge, leaving little room for error. The cost of accurately predicting the MCP increases, discouraging bidders with limited information from participating. As a result, dominant producers can exploit their informational advantage. The costs of estimation are further boosted by the increasing share of renewable energy and their intermittent character. Non-truthful bidding reduces transparency and makes it hard for regulators to identify market power (Kahn et al. 2001).

B. Willems and Y. Yu (2022) analyze the markup not as a result of market power but the need to recoup total costs. In the long run, the revenue of base-load

producers is depressed at high-demand realizations, resulting in a decrease in investment incentives and the distortion of the generation mix.

The dominant producer's exploitation of their informational advantage under the complex auction design is highlighted by P.D. Klemperer (2002) and D. Harbord and C. McCoy (2000). V. Grimm et al. (2008) further argues that the high strategic complexity of the PAB set-up can lead to irrational behavior. The reason why PAB is considered less subject to collusion is that bidders cannot use low inframarginal bids as costless threats (Fabra 2003). P.D. Klemperer (2002) argues that the observation of higher prices being paid to high marginal cost producers creates incentives for low marginal cost producers to include a markup in their bid.

Monopolistic competition

In monopolistic competition, due to the interdependence between low demand realizations and high demand realizations, the monopolist engages in second-degree price discrimination, resulting in monopolistic profits and reduced customer surplus according to G. Federico and D. Rahman (2003).

Experimental studies

D. Engelmann and V. Grimm (2009) highlight two types of untruthful bidding prominent in PAB pricing: high flat bidding, when there is little competition, and supply inflation when the degree of competition is high. High flat bids can improve the bidder's revenue, since the prices received for all units sold are brought closer but incur the risk of being completely priced out by rivals. Supply inflation, rather than high flat bidding, allows bidders to avoid zero gain outcomes.

Empirical and simulation results

An empirical analysis conducted by S. Heim and G. Götz (2021) reveals abusive market power exploitation in the German reserve power market, which operates under the PAB auction design. The study suggests that PAB does not prevent collusion and the problem of strategic capacity withholding and can even exacerbate these problems in markets with sufficient market power. Simulation studies conducted by A. Hailu and S. Thoyer (2010) and J. Bower and D. Bunn (2001) confirm the presence of supply inflation and high flat bidding in PAB pricing. Additionally, L. Sugianto and K. Liao (2014) demonstrates that PAB complicates the learning process for bidders.

3.1.3. Discriminatory vs. uniform pricing

In this section, we directly compare two pricing rules: DP and UP. We employ various metrics, including prices, productive efficiency, consumer surplus, and additional arguments related to market power and consumer expenditures.

Prices

The literature suggests that DP auctions generally result in lower average prices compared to UP (Tenorio 1997; Hudson et al. 2000; Xiong et al. 2004; Fabra et al. 2006; Holmberg 2009; Fabra et al. 2011; Ausubel et al. 2014; Sugianto, Liao 2014; Viehmann et al. 2021; Cheng et al. 2022; Zhao et al. 2023). However, there are cases where UP achieves lower average prices, as highlighted by J. Bower and D. Bunn (2001), D.E. Aliabadi et al. (2017), S.F. Tierney et al. (2008), G. Federico and D. Rahman (2003), and B. Willems and Y. Yu (2022). Despite these exceptions, the majority of investigated cases indicate that DP auctions tend to result in lower average prices, providing political relief in the context of an asymmetric oligopoly.

Productive efficiency

Regarding productive efficiency, the results are mixed. Analytical papers demonstrate that under perfect competition and monopolistic setups, UP leads to higher efficiency (Willems, Yu 2022; Federico, Rahman 2003). This result also holds for the duopoly case, as shown by N. Fabra et al. (2002). Even in the oligopolistic case with learning behavior incorporated, L. Cheng et al. (2022) found that UP produces higher productive efficiency. Simulation studies by D.E. Aliabadi et al. (2017) and J. Viehmann et al. (2021) also support the higher productive efficiency of UP. However, L.M. Ausubel et al. (2014) determined that DP achieves higher efficiency in the asymmetric case with flat demand and decreasing marginal utility. While the evidence is mixed, the prevailing consensus leans towards UP's favoring productive efficiency in various scenarios.

Consumer surplus

There are conflicting findings regarding consumer surplus. B. Willems and Y. Yu (2022) found that UP leads to higher consumer surplus in a model with elastic demand and a wide range of technologies under perfect competition. But N. Fabra et al. (2002) (for symmetric duopoly), P. Holmberg (2009) (for symmetric oligopoly), and G. Federico and D. Rahman (2003) (for monopoly and perfect competition) established that DP produces higher consumer surplus. Additionally, D.E. Aliabadi et al. (2017) finds lower consumer surplus for UP. These conflicting findings highlight the complex relation between pricing rules and consumer surplus.

Additional arguments

In addition to the metrics discussed above, other arguments come into play when comparing DP and UP. The literature suggests that exploiting market power is more challenging in DP auctions than in UP (Federico, Rahman 2003). Furthermore, S.F. Tierney et al. (2008) argues that transitioning from UP to DP auctions could increase consumers' overall expenditures due to strategic bidding

behavior, inefficient plant dispatch, and inefficient capacity investment. These factors need to be considered when evaluating the impact of different pricing rules on consumer welfare.

In summary, the comparison of UP and DP reveals contrasting findings across different metrics. While DP auctions tend to result in lower average prices and potentially higher consumer surplus, the long-term perspective and investment decisions often favor UP (Willems, Yu 2022). Additionally, UP tends to be associated with higher productive efficiency in various scenarios. The difficulty of exploiting market power in DP auctions and the potential increase in consumer expenditures during the transition from UP to DP are also important considerations. Therefore, the choice between these pricing rules should be based on a comprehensive evaluation of these factors and their implications within the specific context of the electricity market.

3.1.4. Vickrey auction pricing

The Vickrey auction, based on the fundamental insight of W. Vickrey (1961), ensures truthful bidding as the dominant strategy for each player since the price received is independent of their bid. Although the Vickrey auction has yet to be implemented in practice, it has been extensively studied both theoretically and experimentally. Originally designed for single-unit auctions, a modified version called the Vickrey–Clarke–Groves (VCG) pricing rule (Clarke 1971) has been proposed for multi-unit electricity market auctions.

In the VCG setup, a bidder's payoff depends on their bids only to the extent that it affects their probability of being chosen. Generators are incentivized to offer supply at a price equal to marginal cost, as it maximizes their probability of operating, ensuring an efficient dispatch and rendering demand reduction irrational.

The specific implementation of the VCG mechanism varies across the academic literature, but the general method is as follows: starting with the cleared market, where all winning bids and the MCP are known, the price for each unit is not based on the MCP or the bid price. Instead, it is determined by the opportunity costs, representing the value that sellers forego by participating in the auction. More precisely, the price for a unit is determined by the value of the highest losing bid for that unit, reflecting the benefit forgone by the seller.

The VCG mechanism benefits the efficiency and simplifies the bidding strategies, as bidding truthfully becomes the dominant strategy (Sessa et al. 2017).

Analytical studies

N. Fabra et al. (2002) conducted a discrete, multi-unit auction model assuming a duopoly and concluded that VCG auctions guarantee productive efficiency

but may result in large payments to firms. V. Grimm et al. (2008) highlighted the potential of VCG to achieve cost-efficiency even in oligopolistic settings with technical restrictions, but they also identified complexity and challenges in price discovery. Their results showed that VCG generates different profits for identical generators and higher prices for larger bidders/generators, which may lead to increased electricity expenditures, incurring high political costs and potentially deterring entry.

Simulation studies

Simulations confirm that bids converge towards truthful bidding in VCG pricing, but there may be sensitivity to heterogeneity among the generators, leading to bid shading (Hailu, Thoyer 2007, 2010).

Comparison to UP and PAB

In the only comparative analytical study (Fabra et al. 2002) considering a duopoly, the welfare ranking between VCG and other pricing rules is inherently ambiguous.

Simulation comparisons largely support VCG pricing. In interesting cases simulating an asymmetric oligopoly, VCG pricing provides prices between those of UP and DP, with the lowest level of price volatility, as shown by L. Sugianto and K. Liao (2014) and S. Lange et al. (2022) in their agent-based simulations. Furthermore, S. Lange et al. (2022) demonstrated that bid shading can increase generators' profits in a VCG auction. However, minor adjustments can render such behavior unprofitable, leading to increased market efficiency and participation. Indeed, S. Lange et al. (2022) proposed a twisted VCG auction that preserves bidders' privacy and guarantees truthful bidding even in an asymmetric oligopoly.

In the case of a symmetric oligopoly, both UP and W. Vickrey pricing result in the lowest average prices, but DP results in the lowest degree of market power and price volatility (Sugianto, Liao 2014). This holds even when considering a more realistic way of capturing generators' learning effects using an Ant Colony Optimization algorithm (Azadeh et al. 2010).

To summarize, the Vickrey auction, through its VCG variant, offers the advantages of efficient dispatch, truthful bidding, and simplified strategies. Analytical and simulation studies highlight the potential benefits and challenges associated with VCG pricing, emphasizing its efficiency and potential for reducing costs. Comparative studies demonstrate that VCG pricing can result in prices and market dynamics between those resulting from UP and DP, with lower price volatility. However, careful considerations of market structure, heterogeneity among generators, and potential gaming strategies are necessary for its effective implementation.

4. Conclusion

This comprehensive literature review addresses the ongoing discussion surrounding pricing rules in the day-ahead market, driven by a significant increase in electricity prices in 2022. The analysis reveals two distinct perspectives based on the general outlook of the electricity market: the political perspective, which prioritizes low electricity costs to protect customers irrespective of future market structure or generation mix, and the efficiency-theoretic perspective, which aims at establishing a well-functioning market that converges towards a fully liberal, self-regulating system despite inherent limitations. These perspectives can lead to different conclusions regarding the choice of a pricing rule.

The pricing rules investigated in this study are uniform pricing (UP), discriminatory pricing (DP), and the Vickrey–Clarke–Groves (VCG) pricing rule. UP, currently the predominantly implemented rule, offers advantages such as transparency, facilitating price discovery, coordination benefits for Over-the-Counter (OTC) contracts, and simplicity, contributing to efficient market operations and reduced transaction costs. However, in the case of imperfect competition, it incentivizes collusion and bid shading, leading to an inefficient dispatch, lower consumer surplus, and possible price spikes, resulting in higher volatility. On the other hand, it benefits smaller bidders and renewable generators as well as converges quickly to perfect competition, albeit with an inefficient dispatch. It also incurs high political costs.

DP, motivated by the goal of reducing wholesale electricity prices and perceived as less susceptible to strategic manipulation by large traders, faces its own challenges. Analytical studies indicate that even under perfect competition, generators include markups in their bids, leading to reduced productive efficiency, consumer surplus, and social welfare. The "guessing the market clearing price" game triggered by DP undermines truthful bidding and results in an inefficient dispatch and reduced production efficiency. Small generators face burdensome estimation costs, while dominant producers can exploit their informational advantage. Empirical and simulation results reveal the existence in markets operating under discriminatory pricing of an abusive exploitation of market power, collusion, supply inflation, and complications in learning.

The Vickrey auction, particularly the VCG pricing rule, ensures truthful bidding even under asymmetric oligopolistic markets. However, it requires side payments and can result in significantly different payments favoring large generators. This incurs high political costs and may potentially increase market power in the long run.

Direct comparison of the three pricing rules finds varying performance across relevant metrics. In terms of average prices, they are minimized under DP, followed by VCG and UP. However, the higher prices in UP actually encourage entry by

smaller bidders and renewable generators, which is promising. Regarding price volatility, VCG is the dominant pricing rule, followed by DP and then UP. In terms of productive efficiency, VCG outperforms the others, followed by UP.

In conclusion, the choice of the pricing rule in the day-ahead market depends on the desired outcomes. While each pricing rule has its advantages and disadvantages, further research and careful analysis are needed to determine the most suitable approach that balances efficiency, fairness, and the long-term sustainability of the electricity market.

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Summary

This literature review delves into the intricate realm of pricing rules in the day-ahead electricity market, spurred by a notable surge in 2022 electricity prices. Employing a comparative analysis of uniform pricing (UP), discriminatory pricing (DP), and the Vickrey–Clarke–Groves (VCG) pricing rule, the study navigates the complexities of these mechanisms. The evaluation unveils contrasting perspectives: the political push for consumer-friendly low prices versus the efficiency aspiration for a self-regulating market. DP, minimizing average prices but increasing volatility, and VCG, excelling in productive efficiency, are pitted against UP, the prevailing yet imperfect norm. The findings underscore the nuances of each rule; DP leads to reduced average prices and heightened volatility, while VCG ensures superior productive efficiency. Despite UP's simplicity, it prompts inefficiencies and political costs. These insights illuminate the pivotal choice faced by policymakers, balancing efficiency, fairness, and market sustainability.

JEL codes: D47, L94, L50

Keywords: *day-ahead market, uniform pricing, discriminatory pricing, Vickrey–Clarke–Groves*

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Cumming, F. (1999) 'Tax-free savings push', Sunday Mail, 4 April, p. 1.

All the items cited in the main text, and no other items, must be placed in the list of references.

Authors should include 2–3 JEL codes with manuscript during submission. For more details on the JEL classification system CLICK HERE.

Information about the journal and the deadlines for submitting articles for next issues are presented at

http://www.managerial.zarz.agh.edu.pl

Double blind peer review procedure

1. In order to assess a quality of submitted publication the Editorial Board consults at least two outside referees (not affiliated to any of the authors' institutions) which are recognized experts in the specific field.

2. At least one of the referees must represent a foreign institution (i.e. an institution located in other country than the home institution of each author).

3. The journal uses double blind peer review policy, i.e. neither the author nor the referee knows the identity of the other. In addition, each referee signs a declaration of no conflict of interests, whereby the conflict of interest is defined as a direct personal relationship (kinship to the second degree, legal relationships, marriage) or a professional scientific cooperation between the referee and the author which took place at least once in the past two years preceding the year of accepting the invitation to review.

4. Only written referee reports are considered (journal does not accept face-to-face or phone-call- based reports). Each report should clearly express the referee's final recommendation (i.e. whether the article should be accepted for publication, revised or rejected). The referees are kindly requested to fill the review form which can be found in "For reviewers" section. In general, the referees are asked to:

– assess:

- the scientific importance of the submission's topic,
- the quality of research;

– verity whether:

- the Abstract is concise and informative,
- the facts and interpretations are satisfactorily separated in the text,
- the interpretations and conclusions follow from the data,
- the length and structure of the paper is appropriate,
- the paper can be shortened without loss of quality,

- all the tables and figures are necessary,
- the diagrams and photographs are of good quality,
- there are all essential figures that should be prepared,
- all the references are exact,
- the manuscript requires proof reading by native speaker,
- there is sufficient attention given to previous research.

5. The names of the referees of particular articles are classified.

6. Once a year the journal publishes the complete list of referees.