WOOD RESEARCH doi.org/10.37763/wr.1336-4561/68.3.600618
ISSN 1336-4561 e-ISSN 2729-8906
68(3): 2023 600-618 pp.

OPTIMISATION OF ENERGY CONSUMPTION IN PAPER PRODUCTION. REVIEW

ŠTEFAN BOHÁČEK, ANDREJ PAŽITNÝ, STELA SLÁMOVÁ
PULP AND PAPER RESEARCH INSTITUTE
SLOVAK REPUBLIC

(RECEIVED MARCH 2023)

ABSTRACT

This article examines the current state of research on energy efficiency in the paper industry, focusing on the key strategies, technologies, and best practices for improving energy efficiency and reducing greenhouse gas emissions. The review covers a range of topics, including energy management systems, process optimisation, cogeneration, waste heat recovery, and renewable energy sources. Overall, the energy efficiency improvements can significantly reduce energy costs and carbon emissions in the paper industry. Still, there is a need for more comprehensive and integrated approaches that consider the entire value chain of paper production.

KEYWORDS: Energy efficiency, optimisation, paper industry, sustainability, energy intensity.

INTRODUCTION

The paper industry is the fourth largest industrial user of energy consuming significant amounts of energy to produce pulp and paper products, mainly in the form of steam and electricity derived from biofuels and partly fossil fuels, primarily natural gas. The increasing demand for paper products has increased energy consumption, making optimising energy in paper production crucial. The optimisation of energy in paper production is not only beneficial for reducing energy consumption and improving profitability but also for enhancing environmental sustainability. Approximately two-thirds of the final energy consumption in pulp and paper industry is fuel used to produce heat, while the remaining third is purchased or self-generated electricity (IEA 2008a). Unlike most other industries, the pulp and paper industry also produce energy as a by-product, generating about 50% of its energy needs from biomass residues (IEA 2006). Between 2004 and 2007, energy became one of the key cost components in Europe's pulp and paper sector (CEPI 2007).

The paper industry's energy-intensive nature makes it imperative to develop energy-efficient processes that reduce energy consumption and improve overall production efficiency. Various methods have shown significant energy savings, such as modifying the kraft process and optimising steam and condensate systems. Additionally, upgrading outdated machinery with modern, energy-efficient models can yield substantial energy savings. It is known that companies including paper mills that incorporate a focus on improving energy efficiency in their lean efforts can also achieve significant operating cost reductions (McKinsey & Company 2010).

MATERIAL AND METHODS

The review methodology involves systematically searching, analysing and synthesising existing research on the topic. The procedure was as follows: *(1)* Defining research questions on the given topic – How big are electricity and energy consumption during paper production? What are the EU's plans and strategies for the future in terms of sustainability? What are the possibilities of optimising energy consumption in paper production? *(2)* Conducting a systematic literature search using appropriate keywords such as energy intensity and efficiency, consumption, sustainability, and energy saving. *(3)* Selection of relevant articles that met specific criteria – relevance to the research question, peer-reviewed, publication date, credibility of the source. *(4)* Analysis and synthesis of data from selected articles, extracting essential information and identifying similarities and differences.

Finally, the key findings were summarised, and the review was composed according to a clear and logical structure emphasising clarity, precision and comprehensibility.

Sustainable paper manufacturing

Sustainability is a balance between the environment, justice and the economy, but the most frequently cited definition comes from the United Nations World Commission on Environment and Development: Sustainable development is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs (United Nations 2023). Sustainable paper manufacturing refers to the production of paper in a way that reduces or eliminates the use of natural resources, reduces waste, and promotes environmentally friendly procedures throughout the entire production process of paper. This includes the sourcing of raw materials, energy consumption and reuse, water conservation, material recycling, waste reduction and reduction of water pollutants and energy consumption (Wen et al. 2015). Through innovations in technology and the implementation of sustainable practices, the paper manufacturing industry is beginning to shift towards a more sustainable future.

In paper industry, sustainability is achieved through new BAT (Best Available Techniques) and innovative materials such as non-wood pulp and auxiliary mixtures (e.g. retention agents) which were developed for their application in pulp stock. New types of fibrous lignocellulosic materials such as distillery refuse, multi-component retention systems, rice straw were suggested for mixture with wood pulp (Pažitný et al. 2011), for modification of properties of pulp suspension (Kuňa et al. 2016) and application for wastewater recycling (Jagaba et al. 2022), respectively. Application of inorganic minerals and organic polymers for elimination of sticky impurities "macrostickies" in the processing of recovered paper was also well described in literature (Hubbe 2000). The application of suitable inorganic and organic agents for eliminating sticky impurities "macrostickies" improves the properties of the recycled fibres suspension and creates better conditions for paper dewatering at the site of the paper machine. Elimination of macrostickies in the fabric preparation process contributes to increasing the runnability of the paper machine and thus to the sustainability of process (Putz 2000, Kuňa et al. 2018). The process of alkaline delignification of disintegrated particle boards and oriented strand boards was studied although these methods are mostly applied to conventionally produced wood pulp (Balberčák et al. 2018). Waste particleboards and oriented strand boards can be used for the production of fibre utilizable for paper manufacturing after removal of various types of adhesives or additives (Wang and Sun 2002, Mo et al. 2003, Risholm-Sundman and Vestin 2005). In general, wood waste may be a bit an interesting source of raw material for pulp and paper industry as well (Ihnát et al. 2020).

In September 2015, at the United Nations General Assembly, countries worldwide signed up for the 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals (SDGs) (European Commission 2023). Some of mentioned SDGs are related to Industry, innovation and infrastructure, Responsible consumption and production, Climate Action (United Nations Department of Economic and Social Affairs 2023). Currently, as a response to national and international regulations and increasing pressure to develop the sustainability of society, companies are gradually adopting directives in their organisations regarding social and environmental responsibility strategies, structures and management systems (Dinçer et al. 2022). Transnational initiatives such as the Sustainable Development Solutions Network (SDSN) advocate for these needs to overcome cross-sectoral constraints between social, environmental and financial issues and avoid concepts and approaches to sustainability which are too individualistic (Butler et al. 2011). Beusch et al. (2022) pointed out that sustainable development cannot be achieved through unilateral policies but requires a total effort at all levels of society, including the environment and finance. Dinçer et al. (2022) believe any foreseeable permanent state would result from interactions between organisations, individuals, society and nations. Scientists believe that achieving sustainability requires a comprehensive approach, which requires financial, social and environmental capabilities, as well as managing the tensions, trade-offs and synergies between these aspects as an overall consequence of sustainability (Jassem et al. 2021, Beusch et al. 2022, Dinçer et al. 2022). From the point of view of financial and environmental sustainability, it is advisable to find innovative ways of manufacturing of fine chemicals based on lignocellulosic materials. Many of them are being used in paper industry. The good example is nanocellulose or nanofibrillated cellulose which has multiple utilization in paper industry (Halaj et al. 2022). The nanocellulose is the strongest part of the plant, so it is typical natural compound present in the cell wall (Poulose et al. 2022). Nanocellulose is generally classified as cellulose nanocrystal (CNC), nanofibrillated cellulose (NFC), or cellulose nanofibrils (CNF) based on their dimensions, functions, preparation methods employed, and the source of production (Thomas et al. 2021). Those fine chemicals can be used as strength additive (Zeng et al. 2021), coating agent for food packaging paper (Jin et al. 2021) or for reduction of fibre content while delivering the commercially required strength of paper (Zambrano et al. 2020). Nanocellulose can be isolated from a variety of cellulosic sources, it is characterized by a significantly higher specific surface area, covered with a surface charge (Gardner et al. 2008).

In addition to the use of new materials and innovations in industrial processes in pulp and paper manufacturing, computerized data processing can be used. Various methods utilising the system of neural networks may become a possible solution, as it also makes it possible to adapt a mathematical model obtained from laboratory experiments to plant equipment, e.g. in delignification process (Boháček 1997). In general, pulp and paper can be characterized by means of artificial neural networks (Almonti et al. 2021). Artificial neural network has good utilization in connection with near infrared spectroscopy of cellulose pulp due to a large amount of data obtained in rapid methods of spectral analysis. Through an artificial neural network based on spectral data, it is possible to predict the water content of pulp in drying stages of paper preparation (Costa et al. 2019). It should be recalled here that NIR spectroscopy has been widely and successfully applied in the pulp and paper industry to monitor the moisture content or basic weight under on-line conditions (Tsuchikawa and Schwanninger 2013). For many other parameters considered in pulp and paper manufacturing and evaluable through artificial neural networks NIR spectroscopy has the significant potential, e.g. pulp yield (Kipuputwa et al. 2010), Kappa number (Downes et al. 2010) and mechanical and optical properties (Fardim et al. 2005). Sustainable paper manufacturing from the point of view of artificial neural networks and artificial intelligence (AI) applications includes utilization of all data obtained during paper production and their good correlation with spectral analysis results.

Policy

The principal direct environmental impacts of the paper industry are associated with its consumption of raw materials, including primary energy resources, and its emissions to air, water, and land. In Europe, waste paper comprises about 35% of household waste by volume (Virtanen and Nilsson 1993). There is also a significant induced impact on forest ecosystems from the demand for pulpwood. These impacts contribute to numerous local, regional, and global environmental and human health problems. Policies are being implemented at European and national levels to promote particular measures in the pulp and paper sector, even though there is no scientific consensus on their environmental impacts. This is a typical example of policy-making being ahead of scientific knowledge, with all its potential consequences. Policy measures include alternative silviculture practices, pulping and bleaching processes, means of waste disposal, product specifications and recycling levels (Bloemhof-Ruwaard et al. 1996). These measures have implications for the geography of production, firm profitability and industrial and trading performance. Because of their high potential impact, policy measures must be consensual, transparent, consistent, and efficient. For this, an assessment methodology is needed that satisfies these same criteria. Such a methodology would permit more systematic policy-making based upon a comprehensive assessment of the potential environmental improvements given available technologies and future new technologies.

Most existing analytical approaches start with a proposed policy instrument and identify environmental (and occasionally trade and industrial) implications (Jerkeman 1993). In the case of the pulp and paper industry, an optimal configuration would consist of a mix of different pulping technologies, the geographical distribution of pulp and paper production, and a level of recycling consistent with the lowest environmental impacts.

Energy intensity

Energy intensity is a way of measuring energy efficiency. It is defined as the amount of energy required to produce a given amount of product or service. It can be calculated as energy consumption per unit of gross domestic product (GDP) (Li and Feng 2009, Zhou et al. 2021). It tries to create a relationship between inputs (energy costs in production) and outputs (all manufactured goods and services). Higher energy intensity means more energy is needed to generate certain economic gains. Conversely, lower energy intensity means less energy is required to create certain economic gains. The reduction of energy demand benefits mainly from the improvement of energy efficiency and structural changes (Voigt et al. 2014, Zeng et al. 2014, Chontanawat et al. 2014). Energy efficiency is influenced by technology and the level of management (Backlund et al. 2012, Wang et al. 2014). Structural changes include changes in industry structures, energy and final demand, for example, the transition from energy-intensive to low-energy industries (Li and Tao 2017, Zhang 2019). In addition, energy demand can also be influenced by behavioural factors, climatic factors, etc. (Filippini and Hunt 2012, Yu et al. 2011). Understanding energy efficiency leads to the sustainable development of the company. A decrease in energy intensity improves energy efficiency by isolating certain influencing factors (Fan et al. 2007, Sue Wing 2008). Due to concerns about a long-term dependence on fossil fuels and the catastrophic consequences of climate change, especially since the energy price crisis of the 1970s, global energy policies have two basic principles: *(1)* increasing the use of renewable energy sources; *(2)* reducing energy intensity.

As a result, the global share of renewable energy sources in total primary energy consumption has increased by an average of 2% per year since 1990, reaching 13.5% in 2018, while there has been a significant decrease in global energy intensity (International Energy Agency 2020a), mainly due to the response of developed economies to the oil price crises of the 1970s (Greening et al. 1998, Liddle 2012, Grossi and Mussini 2017). Various studies further attribute this decline in global energy intensity to two main factors: efficiency and structural effects (Haas and Kempa 2018). The first suggests that the decline is due to the spread of energy-saving technologies in the economy of industrial processes including paper industry, and the second attributes it to a change in industry composition in favour of less energy-intensive industries. Furthermore, Mulder and de Groot (2012) analysed the energy intensity dynamics of 50 sectors in 18 OECD countries. Similarly, they found that between 1970 and 2005, the efficiency effect dominated the decline in energy intensity. Energy intensity in pulp, paper, printing and publishing industry as a whole declined by 3.5 times, however, individual pulp and paper industry declined by 4.8 times. This made the pulp and paper industry one of the most progressive in terms of energy intensity declination.

On the other hand, Löschel et al. (2015) report differences in results in individual EU countries regarding the driving forces of the decrease in energy intensity. Voigt et al. (2014) showed that the efficiency effect is the primary driver of energy intensity dynamics in most industrial economies. However, changes in the composition of sectors have had a more significant benefit in some industrial countries, including Japan, the US and Australia (Voigt et al. 2014).

Energy efficiency

Energy efficiency is considered a key element in sustainable development. It mainly reduces energy resource depletion rates and mitigates greenhouse gas emissions. Therefore, energy efficiency is a central greenhouse gas abatement option at low specific costs. Strong decoupling of economic activity and energy use is a consequence of technical energy efficiency gains and structural change (IEA 2008b). The 2030 Agenda, together Paris Agreement on Climate Change, are the roadmap to a better world and the global framework for international cooperation on sustainable development and its economic, social, environmental and governance dimensions (European Commission 2023). The Paris Agreement is a legally binding international treaty on climate change. It entered into force on 4 November 2016 (European Council 2023). Its overarching goal is to hold the increase in the global average temperature to well below 2°C above pre-industrial levels. The Paris Agreement is a landmark in the multilateral climate change process because, for the first time, a binding agreement brings all nations together to combat climate change and adapt to its effects (United Nations Climate Change 2023). The European Green Deal represents the European Commission's plan for the ecological transformation of the European Union's economy in the interests of a sustainable future. It should describe a tool for facing increasingly frequent and demanding environmental and climate change challenges and turning them into opportunities. The primary goal of the European Green Deal is to ensure that by 2050 Europe will be the first-ever climate-neutral continent. This long-term goal means that by 2050 the net emissions of greenhouse gases produced by the European Union member states will equal zero (Ministry of Environment of SR 2023). The package includes initiatives on climate, environment, energy, transport, industry, agriculture and sustainable finance, all of which are closely linked (European Council 2022).

The European paper industry has already delivered a successful decoupling of carbon emissions from economic growth while reducing carbon emissions by 29% from 2005 to date, having product volumes increased and proved the climate friendliness of its products thanks to certified raw materials and a world class performance in recycling. Objective of CEPI is to be the most competitive, innovative and sustainable provider of net-zero carbon solutions in 2050, namely by strengthening the role of wood and wood-based products, substituting critical or CO_2-intensive raw materials and fossil energy and closing material loops by boosting collection and recycling. As it was already mentioned, the paper industry is the fourth largest industrial energy consumer in Europe. Before the energy crisis, this sector was a net buyer of about 40 TWh of electricity. Around half of the electricity consumed by this sector is produced on-site via highly efficient cogeneration (CHP). Thus, reduction of total costs and improvement of energy efficiency in paper mills as large industrial consumer of energy is linked to two industrial solutions for the most effective reduction of energy consumption: cogeneration units by production of heat and electricity (Qu et al. 2014) and heat recovery systems with high heat recovery efficiency (Pažitný et al. 2013, Wallin and Claesson 2014, Pažitný et al. 2015a,b, Pažitný et al. 2017) with various patented improvements (Pažitný et al. 2021). Paper industry is the largest industrial consumer and generator of renewable energy with biomass coming from side streams of the activities accounting for almost 61% of fuel mix (Rybak 2023). The mentioned policies and their objectives are based directly on the Green Deal.

The EU forest strategy for 2030 is one of the flagship initiatives of the European Green Deal. The strategy sets a vision and concrete actions to improve the quantity and quality of EU forests and strengthen their protection, restoration and resilience. It aims to adapt Europe's forests to the new conditions, weather extremes and high uncertainty brought about by climate change (European Commission – Forests 2023). As specified in the EU forest strategy for 2030, the EU aims to: *(1)* protect forests and the value of the many ecosystem services they provide; *(2)* plant at least 3 billion additional trees in the EU by 2030; *(3)* contribute to a modern, climate-neutral, resource-efficient and competitive economy; *(4)* preserve lively rural areas and help maintain wealthy rural populations; *(5)* ensure that products consumed in the EU do not contribute to global deforestation.

The paper industry is considered energy-intensive, with energy costs between 16% and 30% of total production costs (European Commission 2021, Obrist et al. 2022). Implementing suitable policies might accelerate energy efficiency progress in the future. Davidsdottir (2004) analyses the impact of capital turnover and the vintage structure on energy demand in an econometric model for the US pulp and paper industry. They focus on policy impacts and consider technologies only in a stylised way. A group of studies (Giraldo and Hyman 1995, 1996, Ozalp and Hyman 2006) established an end-use energy demand model based on energy flows for the US paper industry. Although the model is technology-specific, they do not use it to calculate saving potentials through technology improvement. Instead, they focus on allocating energy consumption to the distinct end-users. Szabó et al. (2009) studied the impact of carbon prices on greenhouse gas emissions of the global paper industry. Although their model also contains technical information, like specific energy consumption (SEC), they focus on the market dynamics and paper demand. IUTA (2008) reviewed a large number of technologies and provided guidelines for energy managers, but they did not calculate aggregated saving potentials. Other engineering studies concentrate on single aspects of the paper production chain (Bakhtiari et al. 2010, Laurijssen et al. 2010, Martin 2004). Farahani et al. (2004) analyse the impact of new technologies on CO_2 emissions in the paper industry by comparing Sweden to the US, focusing on the more efficient use of black liquor.

Energy and electricity consumption

The pulp and paper industry presents an energy-intensive sector, which accounted for approximately 6% of global industrial energy consumption in 2017 (International Energy Agency (IEA) 2020b, International Energy Agency (IEA), 2020c, Lipiäinen et al. 2022).

A recent collaboration between associations representing the paper manufacturing (CEPI) and heat pump sectors (EHPA) has resulted in innovation which could produce energy savings of 50% in paper manufacturing. It could also be vital in decarbonising one of Europe's energy-intensive sectors. The industry will continue doing its part in reducing energy consumption, and heat pumps can play an important role. Combined with access to affordable fossil-free energy heat pumps will allow for a full transition towards a decarbonised and circular economy based on bio-products.

The paper industry also has the potential to produce energy, not just consume it. A new study commissioned by CEPI to AFRY, a Scandinavian firm supplying engineering and advisory services, shows the untapped future potential for paper mills to function as renewable energy hubs. The pulp and paper industry could increase its on-site renewable electricity and heat production and sell any excess energy production to the grid, nearby neighbourhoods and other sectors through a "swing capacity effect". The study's authors conclude that by 2030 the pulp and paper industry has the potential to increase its renewable on-site electricity and heat production to generate almost 31 TWh (Rybak 2022). This corresponds to 30% of electricity and nearly 6% of heat generated on-site in 2020. The study also explored the possibility for the paper industry to reduce its consumption and increase the share of renewable energy it provides to the grid, nearby neighbourhoods and possibly other industries. The authors estimate that this 'swing capacity' could regularly reach 10% to 20% for an average paper mill.

Tab. 1 shows individual energy and electricity consumption of CEPI in selected years. The most used resources of primary energy (gas, fuel oil, biomass etc.) were monitored. The most used resource was biomass (693 588 TJ of energy) in year 2020 and the second one was gas (372 509 TJ of energy). 61% of fuels used to produce primary energy in the pulp and paper industry came from biomass. Large amount of the biomass resources is process residues (CEPI Key Statistics 2021).

Tab. 1: Primary energy and electricity consumption in paper industry (CEPI Key Statistics 2021)

Primary energy consumption (TJ)	**1991**	**2000**	**2010**	**2015**	**2019**	**2020**	**% Change 2020/2019**	**% Share of total**
Gas	*259 593*	*404 946*	*489 565*	*395 064*	*385 696*	***372 509***	*-3.4*	*28.9*
Fuel oil	*129 461*	*90 914*	*37 856*	*19 368*	*17 758*	***17 343***	*-2.3*	*1.3*
Coal	*113 867*	*59 304*	*53 280*	*45 925*	*34 981*	***31 937***	*-8.7*	*2.5*
Other fossil fuels	*10 134*	*19 052*	*14 529*	*10 624*	*10 056*	***7 280***	*-27.6*	*0.6*
Biomass[*]	*413 248*	*562 865*	*677 569*	*657 986*	*700 900*	***693 588***	*-1.0*	*53.7*
Other	*3 560*	*4 151*	*8 948*	*12 374*	*22 416*	***24 301***	*8.4*	*1.9*
Total fuel consumption	***929 863***	***1 141 232***	***1 281 746***	***1 141 341***	***1 171 805***	***1 146 960***	***-2.1***	***88.9***
Net bought electricity	***205 852***	***246 864***	***202 945***	***167 381***	***154 795***	***143 557***	***-7.3***	***11.1***
Total primary energy consumption	**1 135 715**	**1 388 096**	**1 484 691**	**1 308 722**	**1 326 601**	**1 290 517**	**-2.7**	**100.0**
Fraction of biomass in Total fuel consumption	**44.4%**	**49.3%**	**52.9%**	**57.7%**	**59.8%**	**60.5%**	**0.7**	**-**
Electricity consumption (GWh)	**1991**	**2000**	**2010**	**2015**	**2019**	**2020**	**% Change 2020/2019**	**% Share of total**
Total electricity produced at site	29 416	41 930	56 780	51 748	50 908	49 900	-2.0	55.6
Purchased electricity	59 045	72 255	67 567	57 838	54 730	52 472	-4.1	58.4
Sold electricity	-1 864	-3 681	-11 193	-11 343	-11 731	-12 595	7.4	14.0
Total electricity consumption	**86 527**	**110 424**	**113 137**	**98 243**	**93 906**	**89 777**	**-4.4**	**100.0**
% of electricity produced through CHP	**88.0%**	**90.4%**	**95.4%**	**96.2%**	**95.7%**	**95.7%**	**-0.1**	**-**

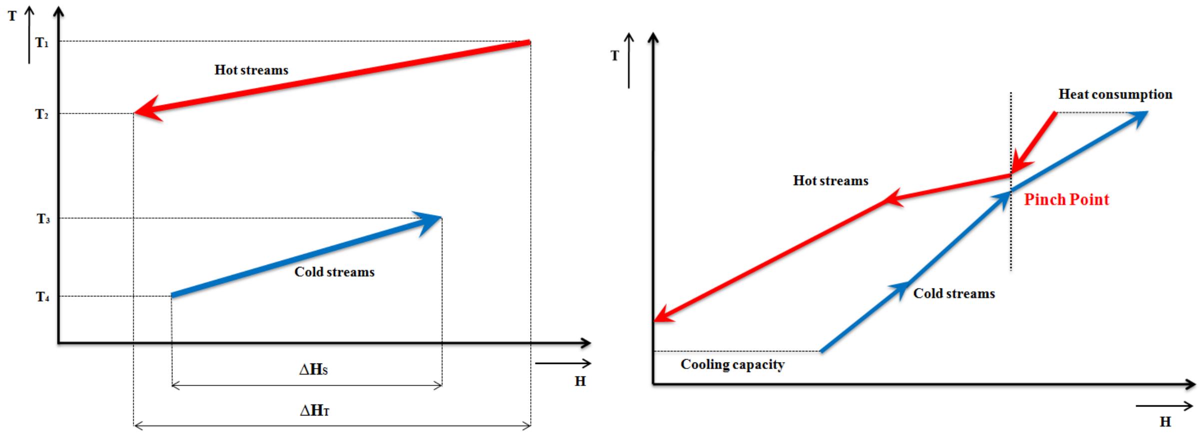
[*] In 2020, 61% of fuels used in the pulp and paper industry came from biomass, large amount of that is process residues.

Installation of heat pumps using Pinch analysis

The early efforts of systematic generation of energy optimal networks between heat exchangers were well described in paper of Linnhoff and Flower in 1978. Since then, pinch analysis based heat integration has been extensively used in the processing (as chemical, petrochemical, pulp and paper, food and drinks, steel making) and power generating industries – more than 40 years. It examines the potential for improving and optimising the heat exchange between heat sources and sinks in order to reduce the amount of external heating and cooling, together with the related cost and emissions. It provides systematic design procedures for energy recovery networks. However, installing heat pumps has a precisely specified area of effectiveness. Therefore, effective heat pump integration into the pulp and paper production technology can only be achieved after a Pinch analysis of the production technology. The procedure includes determining the right place to integrate the heat pump into the production technology to minimise the return on investment and maximise energy savings and pollution reduction (Klemeš and Kravanja 2013).

Basic principles of Pinch analysis

The methodology used stems from the possibilities offered by vector representation of any process stream in the T-H diagram, where the vectors projected on the H axis represent the enthalpy of the current (Fig. 1a).



a) b)

Fig. 1: Schematic representation of a) the hot and cold process stream on the T-H diagram, b) a simple technology on a T-H diagram

Hot technological streams are indicated as those that transport heat to cold streams while entering a specific technological operation at the temperature T_1 and leaving the system at the temperature T_2 (it holds that $T_1 \geq T_2$). The heat content of a stream (ΔH_T - hot stream, ΔH_S - cold stream) depends on the flow rate and specific heat of fluid forming a given stream. As cold technological streams are indicated, those which need to absorb heat are applicable in subsequent processes. T_4 is the temperature of a stream, and T_3 is the target temperature required for technological reasons (also, in this case, the relation $T_3 \geq T_4$ must hold).

The results in the possibility of transforming a complex technology into an explicit dependency during work with which the basic principles of the Pinch theory appeared. By applying these principles in practice, it is relatively easy to arrive at such process modifications that have benefited from the point of view of the entire technology. It excludes possible process modifications that may improve the work of a specific technological node but, from an overall point of view, may even have a negative result due to their negative impact on the further process of the technological unit. Therefore, we can also characterise the outlined approach as a systemic solution to design deficiencies in production technology.

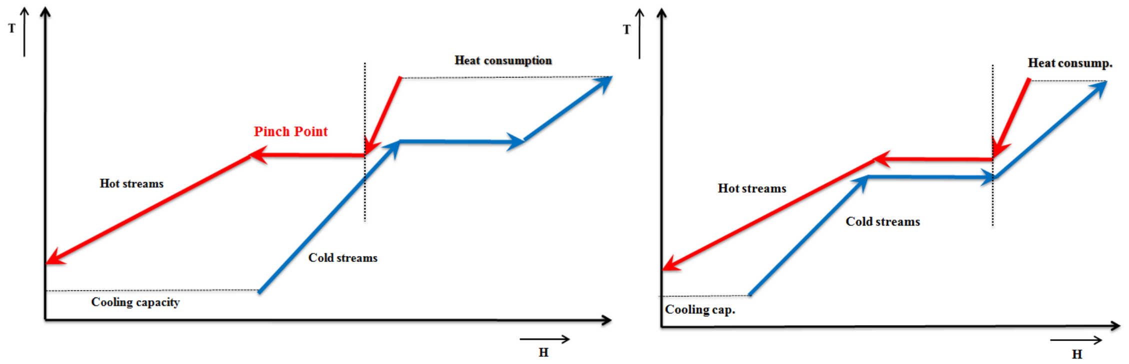
After the technological streams have been portrayed by a vectors addition in the T-H diagram, we obtain an addition curve for so-called hot streams, the temperature of which decreases or is kept constant (as it is, e.g. at steam condensation) and cold streams curve for which the temperature increases or is constant (evaporation can be offered as an example). The curves are referred to as composite curves. The closest gap between these curves is a critical point denoted as the pinch point (Fig. 1b, Linnhoff and Eastwood 1987).

The basic principle of process integration stemming from the "PINCH POINT" theory can be described in a simplified mode by the key equation of this theory:

$$A = T + XP \tag{1}$$

where: A - "actual" is the actual consumption of heat and cold utility, T - "target" is the heat and cold utility consumption attainable following the perfect process integration for a given technology, XP - "cross pinch" is the heat transferred across the pinch point.

The exception is the "reversed" forced heat transport by a heat pump via pinch point. It increases the energy potential of a medium in which work is consumed. Even though normal heat exchange processes must not be installed through the pinch point, the heat pump must be integrated into the system to transfer heat in the opposite direction. The importance of such an installation is especially great if we have a significant process flow from the energy aspect, which is unusable in the given technology and is located just below the pinch point. A significant heat consumer is located above the pinch point (Fig. 2).



a) *b)*

Fig. 2: Composite curve indicating the suitability of heat pump installation (a), after heat pump installation (b)

After installing the heat pump in such a case, the total heat consumption of the given production technology is shown on the composite curves of Fig. 2a at the top right. The situation after the installation of the heat pump is shown in Fig. 2b.

It follows from Eq. 1 that after identifying the process causing heat transport through the pinch point, we locate the error in the design of the analysed technology. This error is not detectable by any other methodology. Therefore, process modification eliminating critical heat transport (precisely the opposite as in the case of a heat pump) is the sought-after solution.

Optimisation of energy saving. Examples

(1) Impulse drying improves mechanical dewatering by applying high temperatures in the nip press, thereby reducing water evaporation in the drying section and energy consumption. The impulse dryer can be retrofitted into an existing machine or incorporated into a new one. The technology was invented by Wahren in 1970 and further developed with a paper machine manufacturer (Beloit) in the 80s and 90s (Laurijssen et al. 2010). A new process innovation called rapid consolidation of moist porous webs came up (Wahren 1982). Under Swedish governmental support, an effective R&D program was started at the end of the 90s. The main argument for developing the technology further became the increased machine capacity and reduced capital intensity in new mills (Luiten et al. 2006). *(2)* Steam impingement dryers are another example of energy optimisation. They are comparable to air impingement dryers but differ in drying medium, as superheated steam is used instead of hot air. Energy use is more or less similar to conventional multi-cylinder drying (De Beer et al. 1998). However, since the exhaust air is (low-pressure) steam, it is possible to recover all latent heat, creating a significant potential for heat and energy recovery (Mujumdar and Devahastin 2008). *(3)* In condensing belt (Condebelt) drying, paper is dried in a drying chamber by contact with a continuous hot steel band heated by gas or steam. Vapour travels through wire gauzes and condensates on a cooled steel band on the other side. Valmet has developed the technology, and R&D has been conducted since 1975. Its main advantage is the increased drying rate (5-15 times) and the potential to completely replace conventional machines' drying sections. Steam savings are expected to be 10-20%, while electricity use will remain the same (Martin et al. 2000). *(4)* The widespread availability of powerful computers made it possible to obtain detailed analyses of complex systems quickly and at a relatively low cost. As a result, computer simulation has become a significant tool in designing changes in industries. A simple computer simulation can be used to answer questions such as whether or not the system will meet specified requirements. It answers the question: what is the system's maximum performance, and how should it be designed to achieve maximum performance? Solving an optimisation problem that depends on the output of a simulation model is known as simulation-based optimization (Steponavičė et al. 2014). *(5)* Integration of heat pumps into production technologies (Barco-Burgos et al. 2022). *(6)* Artificial Intelligence applications for paper manufacturing process optimisation (Walas and Redchuk 2021) and utilization of spectral methods for description of predicted parameters such as water content etc. or in general, digitalization of the production processes.

CONCLUSIONS

In conclusion, the review highlights the importance of optimising energy in the paper industry from an environmental and economic perspective. The review mentions various strategies and technologies such as BAT (heat recovery systems), recovery technologies for various lignocellulosic materials utilization, especially non-wood materials, available to improve energy efficiency, reduce carbon emissions, and for lower operational and material costs in the paper industry. However, implementing these measures can be challenging due to various barriers, such as a lack of financial resources, limited awareness of energy management practices, and complex production processes.

A comprehensive approach is needed that considers the entire value chain of paper production to overcome these barriers, from raw materials to finished products. Energy management systems, process optimisation, cogeneration, waste heat recovery, and renewable energy sources are all viable options for improving energy efficiency in the paper industry. Furthermore, the review suggests that adopting innovative technologies, such as digitalisation and artificial intelligence, can help improve energy management practices and enable more efficient and sustainable paper production.

Overall, optimising energy in the paper industry is a complex and multifaceted task that requires collaboration between stakeholders, including paper mills, suppliers, customers, and policymakers. The literature review provides a valuable resource for researchers, practitioners, and decision-makers to understand better the challenges and opportunities for optimising energy in the paper industry.

ACKNOWLEDGMENTS

This publication was created thanks to support within the Integrated Infrastructure 2014 - 2020 operational program for the project: Center of Excellence of the LignoSilva Forestry and Timber Complex (ITMS code: 313011S735), co-financed by the European Regional Development Fund.

REFERENCES

1. ALMONTI, D., BAIOCCO, G., UCCIARDELLO, N., 2021: Pulp and paper characterization by means of artificial neural networks for effluent solid waste minimization - A case study. Journal of Process Control 105, 283-291.
2. BACKLUND, S., THOLLANDER, P., PALM, J., OTTOSSON, M., 2012: Extending the energy efficiency gap. Energy Policy 51, 392-396.
3. BAKHTIARI, B., FRADETTE, L., LEGROS, R., PARIS, J., 2010: Opportunities for the integration of absorption heat pumps in the pulp and paper process. Energy 35, 12, 4600-4606.
4. BALBERČÁK, J., BOHÁČEK, Š., PAŽITNÝ, A., IHNÁT, V., LÜBKE, H., 2018: Chemical processing of waste wood based agglomerates part II: Evaluation of properties of

fluting liners made of semichemical pulp obtained by an alkaline cooking process. Wood Research 63, 1, 35-45.

5. BARCO-BURGOS, J., BRUNO, J. C., EICKER, U., SALDAÑA-ROBLES, A. L., & ALCÁNTAR-CAMARENA, V., 2022: Review on the integration of high-temperature heat pumps in district heating and cooling networks. Energy 239, 122378.
6. BEUSCH, P., FRISK, J. E., ROSÉN, M., DILLA, W., 2022: Management control for sustainability: Towards integrated systems. Management Accounting Research 54, 100777.
7. BLOEMHOF-RUWAARD, J.M., VAN WASSENHOVE, L.N., GABEL, H.L., WEAVER, P.M., 1996: An environmental life cycle optimisation model for the European pulp and paper industry. Omega 24, 6, 615-629.
8. BOHÁČEK, Š., 1997: Optimisation of Oxygen Delignification Using Artificial Neural Networks. Chemical and Biochemical Engineering Quarterly 11, 2, 75-80.
9. BUTLER, J.B., HENDERSON, S.C., RAIBORN, C., 2011: Sustainability and the balanced scorecard: Integrating green measures into business reporting. Management Accounting Quarterly. Winter 12, 2, 1-10.
10. CEPI, 2022: Key Statistics 2021.
11. CEPI, 2023: Press release: A collaboration between the paper industry & heat pump producers could halve its energy needs & help decarbonise the sector.
12. CHONTANAWAT, J., WIBOONCHUTIKULA, P., BUDDHIVANICH, A., 2014: Decomposition analysis of the change of energy intensity of manufacturing industries in Thailand. Energy 77, 171-82.
13. CONFEDERATION OF EUROPEAN PAPER INDUSTRIES (CEPI), 2007: Energy issue sheet. Energy markets, the need for fully liberalised and well-functioning markets in Europe. Confederation of European Paper Industries.
14. COSTA, L.R., TONOLI, G.H.D., MILAGRES, F.R., HEIN, P.R.G., 2019: Artificial neural network and partial least square regressions for rapid estimation of cellulose pulp dryness based on near infrared spectroscopic data. Carbohydrate Polymers 224, 115186.
15. DAVIDSDOTTIR, B., 2004: Capital vintage and climate change policies: The case of US pulp and paper. Environmental Science and Policy 7, 3, 221-233.
16. DE BEER, J., WORRELL, E., BLOK, K., 1998: Long-term energy-efficiency improvements in the paper and board industry. Energy 23, 1, 21-42.
17. DINÇER, H., YÜKSEL, S., MARTÍNEZ, L., 2022: Collaboration enhanced hybrid fuzzy decision-making approach to analyze the renewable energy investment projects. Energy Reports 8, 377–389.
18. DOWNES, G.M., MEDER, R., EBDON, N., BOND, H., EVANS, R., JOYCE, K., SOUTHERTON, S., 2010: Radial variation in cellulose content and kraft pulp yield in *Eucalyptus nitens* using near-infrared spectral analysis of air-dry wood surfaces. Journal of Near Infrared Spectroscopy 18, 2, 147-154.
19. EUROPEAN COMMISSION, 2021: Energy Efficiency in the Pulp and Paper Industry.
20. EUROPEAN COMMISSION, 2023: Forests.
21. EUROPEAN COMMISSION, 2023: The EU and the United Nations – common goals for a sustainable future.

22. EUROPEAN COUNCIL, 2022: European Green Deal.
23. EUROPEAN COUNCIL, 2023: Paris Agreement on climate change.
24. FAN, Y., LIAO, H., WEI, Y.-M., 2007: Can market oriented economic reforms contribute to energy efficiency improvement? Evidence from China. Energy Policy 35, 4, 2287-2295.
25. FARAHANI, S., WORRELL, E., BRYNTSE, G., 2004: CO_2-free paper? Resources, Conservation and Recycling 42, 4, 317-336.
26. FARDIM, P., FERREIRA, M.M.C., DURÁN, N., 2005: Determination of mechanical and optical properties of Eucalyptus kraft pulp by NIR spectrometry and multivariate calibration. Journal of Wood Chemistry and Technology 25, 4, 267-279.
27. FILIPPINI, M., HUNT, L.C., 2012: US residential energy demand and energy efficiency: A stochastic demand frontier approach. Energy Economics 34, 5, 1484-1491.
28. GARDNER, D.J., OPORTO, G.S., MILLS, R., SAMIR, M.A.S.A., 2008: Adhesion and surface issues in cellulose and nanocellulose. Journal of Adhesion Science and Technology 22, 545-567.
29. GIRALDO, L., HYMAN, B., 1996: An energy process-step model for manufacturing paper and paperboard. Energy 21, 7-8, 667-681.
30. GIRALDO, L., HYMAN, B., 1995: Energy end-use models for pulp, paper, and paperboard mills. Energy 20, 10, 1005-1019.
31. GREENING, L.A., DAVIS, W.B., SCHIPPER, L., 1998: Decomposition of aggregate carbon intensity for the manufacturing sector: Comparison of declining trends from 10 OECD countries for the period 1971-1991. Energy Economics 20, 1, 43-65.
32. GROSSI, L., MUSSINI, M., 2017: Inequality in energy intensity in the EU-28: Evidence from a new decomposition method. Energy Journal 38, 4, 1-18.
33. HAAS, C., KEMPA, K., 2018: Directed technical change and energy intensity dynamics: Structural change vs. energy efficiency. Energy Journal 39, 4, 127-152.
34. HALAJ, M., BOHÁČEK, Š., PAŽITNÝ, A., STANKOVSKÁ, M., RUSS, A., 2022: Methods of preparation of nanofibrillated cellulose for special filter papers with effective air filtration. Short notes. Wood Research 67, 2, 340-347.
35. HUBBE, M.A., 2000: Stickies, pitch, and secondary fiber - A chemist's view, in opportunities in wet-end chemistry: Feature Essay.
36. IHNÁT, V., LÜBKE, H., BALBERČÁK, J., KUŇA, V., 2020: Size reduction downcycling of waste wood. Review. Wood Research 65, 2, 205-220.
37. INTERNATIONAL ENERGY AGENCY (IEA), 2006: Energy efficient technologies and CO_2 reduction potentials in the pulp and paper industry. Conference proceedings from the workshop on energy efficient technologies and CO_2 reduction potentials in the pulp and paper industry held on 9th October 2006 at IEA in Paris.
38. INTERNATIONAL ENERGY AGENCY (IEA), 2008a: Worldwide trends in energy use and efficiency. Key insights from IEA indicator analysis. Paris, France: IEA.
39. INTERNATIONAL ENERGY AGENCY (IEA), 2008b: Energy technology perspectives: Scenarios and strategies to 2050. Paris: OECD/IEA.
40. INTERNATIONAL ENERGY AGENCY, 2020a: Renewables 2020. Analysis – IEA.
41. INTERNATIONAL ENERGY AGENCY (IEA), 2020b: Data and statistics.

42. INTERNATIONAL ENERGY AGENCY (IEA), 2020c: Pulp and paper.
43. IUTA, PTS, LTT, EUTECH, 2008: Branchenleitfaden für die Papierindustrie. Duisburg, Institut für Energie- und Umwelttechnik e.V.; PTS Papiertechnische Stiftung; RWTH Aachen Lehrstuhl für Technische Thermodynamik. Eutech Energie & Management GmbH.
44. JAGABA, A.H., KUTTY, S.R.M., BALOO, L., BIRNIWA, A.H., LAWAL, I.M., ALIYU, M.K., YARO, N.S.A., USMAN, A.K., 2022: Combined treatment of domestic and pulp and paper industry wastewater in a rice straw embedded activated sludge bioreactor to achieve sustainable development goals. CSCEE 6, 100261.
45. JASSEM, S., ZAKARIA, Z., CHE AZMI, A., 2021: Sustainability balanced scorecard architecture and environmental performance outcomes: A systematic review. International Journal of Productivity and Performance Management 71, 5, 1728-1760.
46. JERKEMAN, P., 1993: The forest sector in the sustainable society: A pre-study, Jaakko Poyry Client Magazine 1/93.
47. JIN, K., TANG, Y., LIU, J., WANG, J., YEB, CH., 2021: Nanofibrillated cellulose as coating agent for food packaging paper. International Journal of Biological Macromolecules 168, 331-338.
48. KIPUPUTWA, C., GRZESKOWIAK, V., LOUW, J.H., 2010: The use of near-infrared scanning for the prediction of pulp yield and chemical properties of *Pinus patula* in the Mpumalanga escarpment area of South Africa. Southern Forests 72, 3, 181-189.
49. KLEMEŠ, J.J., KRAVANJA, Z., 2013: Forty years of Heat Integration: Pinch Analysis (PA) and Mathematical Programming (MP). Current Opinion in Chemical Engineering 2, 4, 461-474.
50. KUŇA, V., BALBERČÁK, J., OPÁLENÁ, E., PAŽITNÝ, A., RUSS, A., SCHWARTZ, J., 2016: The effect of multi-component retention systems on the properties of the paper suspensions. Wood Research 61, 5, 767-776.
51. KUŇA, V., BALBERČÁK, J., PAŽITNÝ, A., RUSS, A., BOHÁČEK, Š., IHNÁT, V., 2018: Tackiness reducing of the stickies surfaces by inorganic agents and organic polymers. Wood Research 63, 6, 1013-1020.
52. LAURIJSSEN, J., DE GRAM, F. J., WORRELL, E., FAAIJ, A., 2010: Optimising the energy efficiency of conventional multi-cylinder dryers in the paper industry. Energy 35, 9, 3738-3750.
53. LI, L., FENG, W., 2009: The impact factors of energy intensity in Chinese industry. International Conference on Energy and Environment Technology 429-432.
54. LI, M.-J., TAO, W.-Q., 2017: Review of methodologies and policies for evaluation of energy efficiency in high energy-consuming industry. Applied Energy 187, 203-215.
55. LIDDLE, B., 2012: OECD energy intensity: measures, trends, and convergence. Energy Efficiency 5, 583-597.
56. LINNHOFF, B., EASTWOOD, A.R., 1987: Overall site optimisation by pinch technology. Chemical Engineering Research and Design 65, 5, S138-S144.
57. LINNHOFF, B., FLOWER, J.R., 1978: Synthesis of heat exchanger networks: I. Systematic generation of energy optimal networks. AIChE Journal 24, 4, 633-642. (The first and key paper introducing heat integration).

58. LIPIÄINEN, S., KUPARINEN, K., SERMYAGINA, E., VAKKILAINEN E., 2022: Pulp and paper industry in energy transition: Towards energy-efficient and low carbon operation in Finland and Sweden. Sustainable Production and Consumption 29, 421-431.
59. LÖSCHEL, A., POTHEN, F., SCHYMURA, M., 2015: Peeling the onion: Analysing aggregate, national and sectoral energy intensity in the European Union. Energy Economics 52, Supplement 1, S63-S75.
60. LUITEN, E., VAN LENTE, H., BLOK, K., 2006: Slow technologies and government intervention: Energy efficiency in industrial process technologies. Technovation 26, 9, 1029-1044.
61. MARTIN, A., 2004: Energy analysis of impulse technology: Research-scale experimental papermaking trials and simulations of industrial applications. Applied Thermal Engineering 24, 16, 2411-2425.
62. MARTIN, N., WORRELL, E., RUTH, M., PRICE, L., ELLIOTT, R.N., SHIPLEY, A.M., THORNE, J., 2000: Emerging energy-efficient industrial technologies, LBNL-46990. Berkeley, CA: Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory.
63. McKinsey & Company, 2010: Energy efficiency: A compelling global resource. McKinsey Sustainability & Resource Productivity.
64. MINISTRY OF ENVIRONMENT OF THE SLOVAK REPUBLIC, The European Green Deal, 2023.
65. MO, X., CHENG, E., WANG, D., SUN, X.S., 2003: Physical properties of medium-density wheat straw particleboard using different adhesives. Industrial Crops and Products 18, 1, 47-53.
66. MUJUMDAR, A.S., DEVAHASTIN, S., 2008: Superheated steam drying. An emerging drying technology. Presentation at superheated steam drying workshop at the Danish Technology Institute, Denmark.
67. MULDER, P., DE GROOT, H.L.F., 2012: Structural change and convergence of energy intensity across OECD countries, 1970-2005. Energy Economics 34, 1910-1921.
68. OBRIST, M.D., KANNAN, R., SCHMIDT, T.J., KOBER, T., 2022: Long-term energy efficiency and decarbonization trajectories for the Swiss pulp and paper industry. Sustainable Energy Technologies and Assessments 52, Part A, 101937.
69. OZALP, N., HYMAN, B., 2006: Energy end-use model of paper manufacturing in the US. Applied Thermal Engineering 26, 5-6, 540-548.
70. PAŽITNÝ, A., BOHÁČEK, Š., MEDO, P., 2013: Vývoj nových technológií umožňujúcich rekuperáciu tepla a ich aplikácia v papierenskom priemysle, (Development of new technologies for heat recovery and their application in paper industry). Energetika 63, 8-9, 481-483 (in Slovak).
71. PAŽITNÝ, A., BOHÁČEK, Š., MEDO, P., BALBERČÁK, J., 2015a: Application of innovative heat recovery unit in paper industry with potential utilization in wood-processing and furniture industry. Wood Research 60, 1, 101-112.
72. PAŽITNÝ, A., BOHÁČEK, Š., MEDO, P., BALBERČÁK, J., 2015b: Optimalizácia spotreby energie poloprevádzkového papierenského stroja aplikáciou moderného

výmenníka tepla, (Optimisation of the energy consumption of a semi-operational paper machine by applying a modern heat exchanger). Energetika 65, 8-9, 450-454 (in Slovak).

73. PAŽITNÝ, A., BOHÁČEK, Š., MEDO, P., BALBERČÁK, J., SCHWARTZ, J., KUŇA, V., IHNÁT, V., 2017: Possibilities of removing condensate from a heat recovery unit utilizable in paper industry. Wood Research 62, 2, 273-282.
74. PAŽITNÝ, A., BOHÁČEK, Š., MEDO, P., BREZÁNIOVÁ, Z., RUSS, A., STANKOVSKÁ, M., IHNÁT, V., SCHWARTZ, J., GIGAC, J., BALBERČÁK, J., 2021: Heat recovery device based on integration of spiral with U-condensate discharge pipe, Pulp and Paper Research Institute, JSC, Bratislava. PP 50043 – 2016 (IPO SR, 28.06.2016, patent No. SK 288838 B6 granted and published on 01.03.2021), TRL 9.
75. PAŽITNÝ, A., BOHÁČEK, Š., RUSS, A., 2011: Application of distillery refuse in papermaking: Novel methods of treated distillery refuse spectral analysis. Wood Research 56, 4, 533-544.
76. POULOSE, A., PARAMESWARANPILLAI, J., GEORGE, J.J., GOPI, J.A., KRISHNASAMY, S., DOMINIC C. D., M., HAMEED, N., SALIM, N.V., RADOOR, S., SIENKIEWICZ, N., 2022: Nanocellulose: A Fundamental Material for Science and Technology Applications. Molecules 27, 22, 8032.
77. PUTZ, J., 2000: Stickies in recycled fiber pulp, in Recycled fiber and deinking, L. Göttsching, Pakarinen, H., Editor, Fapet Oy: Helsinki, Finland, Pp 441-498.
78. QU, M., ABDELAZIZ, O., YIN, H., 2014: New configurations of a heat recovery absorption heat pump integrated with a natural gas boiler for boiler efficiency improvement. Energy Conversion and Management 87, 175-184.
79. RISHOLM-SUNDMAN, M., VESTIN, E., 2005: Emissions during combustion of particleboard and glued veneer. Holz als Roh- und Werkstoff 63, 3, 179-185.
80. RYBAK, M., 2022: Press release: New study shows paper industry could increase on-site renewable electricity and heat generation by 2030, November 29th, 2022.
81. RYBAK, M., 2023: Targeted reform of the Electricity Market Design. Cepi’s position paper, May 11th, 2023.
82. STEPONAVIČĖ, I., RUUSKA, S., MIETTINEN, K., 2014: A solution process for simulation-based multiobjective design optimization with an application in the paper industry. Computer-Aided Design 47: 45-58.
83. SUE WING, I., 2008: Explaining the declining energy intensity of the US economy. Resource and Energy Economics 30, 1, 21-49.
84. SZABÓ, L., SORIA, A., FORSSTRÖM, J., KERÄNEN, J.T., HYTÖNEN, E., 2009: A world model of the pulp and paper industry: Demand, energy consumption and emission scenarios to 2030. Environmental Science and Policy 12, 3, 257-269.
85. THOMAS, S.K., BEGUM, S., MIDHUN DOMINIC, C.D., SALIM, N.V., HAMEED, N., RANGAPPA, S.M., SIENGCHIN, S., PARAMESWARANPILLAI, J., 2021: Isolation and characterization of cellulose nanowhiskers from Acacia caesia plant. Journal of Applied Polymer Science 138, 50213.
86. TSUCHIKAWA, S., SCHWANNINGER, M., 2013: A review of recent near-infrared research for wood and paper (Part 2). Applied Spectroscopy Reviews 48, 7, 560-587.

87. UNITED NATIONS Climate Change, 2023: The Paris Agreement.
88. UNITED NATIONS Department of Economic and Social Affairs, 2023: The 17 Goals.
89. UNITED NATIONS, 2023: Sustainability.
90. VIRTANEN, Y., NILSSON, S., 1993: Environmental Impacts of Waste Paper Recycling. Earthscan, London.
91. VOIGT, S., DE CIAN, E., SCHYMURA, M., VERDOLINI, E., 2014: Energy intensity developments in 40 major economies: Structural change or technology improvement? Energy Economics 41, 47-62.
92. WAHREN, D., 1982: Methods and apparatus for the rapid consolidation of moist porous webs. US Patent 4,324,613, April 13th, 1982.
93. WALAS, F., REDCHUK, A., 2021: IIoT/IoT and Artificial Intelligence/Machine Learning as a Process Optimization driver under industry 4.0 model. Journal of Computer Science and Technology 21, 2, e15.
94. WALLIN, J., CLAESSON, J., 2014: Analyzing the efficiency of a heat pump assisted drain water heat recovery system that uses a vertical inline heat exchanger. Sustainable Energy Technologies and Assessments 8, 109-119.
95. WANG, Z., FENG, C., ZHANG, B., 2014: An empirical analysis of China's energy efficiency from both static and dynamic perspectives. Energy 74, 322-330.
96. WANG, D., SUN, X.S., 2002: Low density particleboard from wheat straw and corn pith. Industrial Crops and Products 15, 1, 43-50.
97. WEN, Z., XU, C., ZHANG, X., 2015: Integrated Control of Emission Reductions, Energy-Saving, and Cost–Benefit Using a Multi-Objective Optimisation Technique in the Pulp and Paper Industry. Environmental Science & Technology 49, 6, 3636-3643.
98. YU, Z., FUNG, B.C.M., HAGHIGHAT, F., YOSHINO H., MOROFSKY E., 2011: A systematic procedure to study the influence of occupant behavior on building energy consumption. Energy and Buildings 43, 6, 1409-1417.
99. ZAMBRANO, F., STARKEY, H., WANG, Y., ABBATI DE ASSIS, C., VENDITTI, R., PAL, L., JAMEEL, H., HUBBE, M.A., ROJAS, O.J., GONZALEZ, R., 2020: Using micro- and nanofibrillated cellulose as a means to reduce weight of paper products: A review. BioResources 15, 2, 4553-4590.
100. ZENG, L., XU, M., LIANG, S., ZENG, S., ZHANG, T., 2014: Revisiting drivers of energy intensity in China during 1997-2007: A structural decomposition analysis. Energy Policy 67, 640-647.
101. ZENG, J., ZENG, Z., CHENG, Z., WANG, Y., WANG, Y., WANG, B., GAO, W., 2021: Cellulose nanofibrils manufactured by various methods with application as paper strength additives. Scientific Reports 11, 11918.
102. ZHANG, T., 2019: Which policy is more effective, carbon reduction in all industries or in high energy-consuming Industries? From dual perspectives of welfare effects and economic effects. Journal of Cleaner Production 216, 184-196.
103. ZHOU, Q., FU, C., NI, H., GONG, L., 2021: What are the main factors that influence China's energy intensity? – Based on aggregate and firm-level data. Energy Reports 7, 2737-2750.

ŠTEFAN BOHÁČEK, ANDREJ PAŽITNÝ, STELA SLÁMOVÁ*
PULP AND PAPER RESEARCH INSTITUTE
DÚBRAVSKÁ CESTA 14
841 04 BRATISLAVA
SLOVAK REPUBLIC
*Corresponding author: slamova@vupc.sk