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SteamDry

D3.1 Vision roadmap of SSD transition

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EXECUTIVE SUMMARY

This vision roadmap for superheated steam drying transition spans from 2024 onwards, starting with fundamental R&D and progressing through pilot, demo and flagship that lead to commercial operations, which extends to work after this project. The roadmap's aim is to develop process concept and plant engineering requirements, and market suitability for SSD technology and identify the needed steps towards the goal. Key milestones include the development of a process concept, plant engineering, and suitability for market products. The creation of the vision roadmap involved collaboration between the partners of the project.

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1 Introduction

This document is a generic roadmap of the transition of different dryers in pulp and paper, nonwoven and wood material industries. Their energy requirements for drying were estimated to be for paper and board 400 PJ, nonwovens 1.4-2.2 PJ and wood drying 70-140 PJ. Paper and board account for the highest energy consumption in drying processes. From these industries papermaking is the logical starting point to start looking for energy savings.

This report gives an overview (Chapters 2 and 3) of existing pulp and paper dryers as well as nonwoven and wood material dryers. The report lists the different dryer technologies, capacities, energy sources and consumptions, and materials to be dried. As a part of this review, typical energy production technologies and CO_2 emission levels of industrial dryers are listed, which are used as a benchmark during the project. Based on existing industrial dryers, estimates of the level of process and dryer changes, and the technical complexity needed for the superheated steam dryer (SSD) modification were made. Possible reuse options for steam generated by SSD are also identified.

In conventional drying processes used in papermaking such as contact cylinder and convective hot air drying, energy efficiency is limited, and CO_2 emissions are inevitable. The SteamDry project's SSD technology offers a paradigm shift by harnessing the superior heat transfer properties of superheated steam. This is presented in Chapter 4. By circulating and reheating steam in a closed loop, the SteamDry system maintains temperatures above the vaporisation point, resulting in lower net energy consumption and the use of surplus steam for other purposes within the facility. This closed-loop system enhances energy efficiency.

Moreover, SteamDry's SSD technology offers several advantages over traditional drying methods. With faster drying rates and shorter drying times, the proposed process minimises product degradation and improves overall product quality. Additionally, the compact design of SSD dryers and the ability to reuse surplus steam for other industrial processes further enhance energy efficiency and operational sustainability. The SteamDry project also emphasises system integration and advanced digitalisation of monitoring and control systems. Through pilot-scale measurements and comparison with commercial best practices, the project will demonstrate the substantial improvement potential of its integrated approach to drying technology. SteamDry is committed to developing cutting-edge drying technology that exceeds current energy efficiency standards, while contributing to a more sustainable future for manufacturing industries. Accordingly, a vision roadmap is presented in Chapter 5. The deliverable is concluded with a summary in Chapter 6.

1.1 Aims of the project

The SteamDry project has several objectives: 1) Developing Energy-Efficient Drying Technology that 2) significantly improves energy efficiency and 3) Achieving CO_2-Emission Free Drying Process, with 4) Advanced Control System for SSD Dryer and 5) piloting SSD Process for Web-like Products. The project also makes 6) Environmental and Techno-economic Assessment of SSD, 7) Evaluates Business Potential for Various Product Manufacturing Sectors and 8) Communicates, Disseminates, and Exploits Project Outcomes.

	CURRENT	STEAMDRY
ENERGY	~1100 kWh/ton	~450 kWh/ton
CO2 (FOSSIL)	0.45 tCO2/t paper	No emissions
HEAT	30-40% lost to air	Latent heat recovered
SOURCE	Combustion	Electricity

Figure 1. Estimated Current Dryer vs. SteamDry Concept.

The development and piloting of SSD technology increase knowledge of keeping two gas phases (air and steam) separate, shows methods to clean biobased particles from the steam and operates these safely with the help of AI-supported advanced control platform. Solutions are considered for existing or newbuilt infrastructure.

Project technology development focuses on following TRL improvements (see Table 1).

Table 1. SteamDry technology development focus.

	Technologies developed in SteamDry	TRL	
		from	to
A	Develop CO2-emission free drying concept	4	6
B	Development of safety measures for pilot	5	6
C	Superheating by Mechanical Vapor Compressor adapted to pilot	5	7
D	Dryer model and heat integration concept for SSD	5	7
E	The superheated steam concept for cylinder dryers in laboratory	4	6
F	Piloting leakage free contactless sealing technology	4	6
G	Piloting steam purification technology	4	6
H	Piloting AI based control system for dryers	4	6
I	Pilot superheated steam concept for selected dryer	4	6
J	Develop drying concept for rebuilds and green-field machines	4	5

2 Drying technologies for web-like materials

Industrial dryers for weblike materials such as paper, board, nonwovens, and veneer are essential for ensuring product quality and efficiency. Contact cylinder dryers, also known as roll dryers, are the most commonly used for drying paper and board. These dryers consist of steam-heated cylinders with smooth outer surfaces. The web material is passed over these cylinders, allowing heat to transfer directly from the cylinder to the material through conduction. Another common type is the convection dryer, which uses hot air to remove moisture e.g. from coated webs and nonwovens. This method is widely used in paper and board production due to its ability to handle large volumes and provide uniform drying. Convection dryers can be designed as through-air dryers, where hot air passes through the material, or as flotation dryers, where the material is suspended on a cushion of air, preventing contact with surfaces and reducing the risk of damage.

Infrared (IR) dryers are another popular choice, especially for nonwovens and coated papers. These dryers use infrared radiation to heat the material directly, providing rapid and efficient drying. IR dryers are particularly useful for applications requiring precise control over the drying process, as they can quickly adjust to changes in material thickness and moisture content.

For veneer drying, roller dryers are commonly used. These dryers consist of a series of rollers that the veneer passes over, similarly getting heated with impinging hot air jets, ensuring even and consistent drying. Roller dryers are effective for thin materials like veneer, as they provide gentle handling and minimize the risk of warping or cracking.

Vacuum dryers are also employed for heat-sensitive materials, including certain nonwovens and speciality papers. By reducing the pressure, these dryers allow for drying at lower temperatures, preventing thermal degradation and preserving the material's properties.

Table 2. Types and typical applications of industrial drying systems.[1]

		Typical applications		
Type	**Hobby**	**Small**	**Medium**	**Large**
Convection-type dryers				
Lumber, timber, poles	x	x	x	x
Veneer, sheets	x	x	x	x
Tray	x	x		
Dehumidification dryers	x	x	x	
Air drying yards	x	x	x	x
Forced air drying		x	x	
Pre-dryers		x	x	x
Radiation dryers		x	x	x
Vacuum dryers	x	x		
High frequency dryers	x	x		
HF + vacuum board dryers	x	x		
HF + convection veneer dryers		x		
Conduction dryers				x
Hydrostatic press dryers		x	x	x
Rotary dryers			x	x
Flash-tube dryers			x	x
Belt dryers		x	x	x
Screw bed dryers		x	x	x
Fluidized bed dyers			x	x

2.1 Drying of paper and board

Typical papermaking process comprises raw material preparation from either virgin or recovered pulp, pulping of it and preparing it for forming. During sheet formation, the pulp is spread evenly on fabric and water is removed first mechanically by draining and pressing, followed by drying where the remaining water is evaporated. After the product is dried, several different types of finishing operations like coating or calendaring and sheeting can be applied. There are large differences between paper mills in their produced grades and feedstock, however typical processes are similar (See Figure 2).

[1] Industrial Drying Systems, Springer 2023, ISBN: 978-3-031-31862-7. https://doi.org/10.1007/978-3-031-31863-4

Figure 2. Typical process steps of papermaking.

Several drying types are used in current papermaking. Among them are cylinder drying, air impingement drying, through air drying and infrared-drying being the main methods used. Paper industry dryer types share has been earlier estimated (Karlsson, 2001[2]) to be 85-90% using cylinder drying, 4-5% using Yankee, 3-4% using infrared, 2-3% impingement and 1-2% through air drying (TAD).

Multicylinder dryer: The conventional and most widely used method of drying paper, which involves passing the wet web through a series of steam-heated cylinders and controlling the moisture content and temperature of the paper. An example of multicylinder dryer is shown in Figure 3.

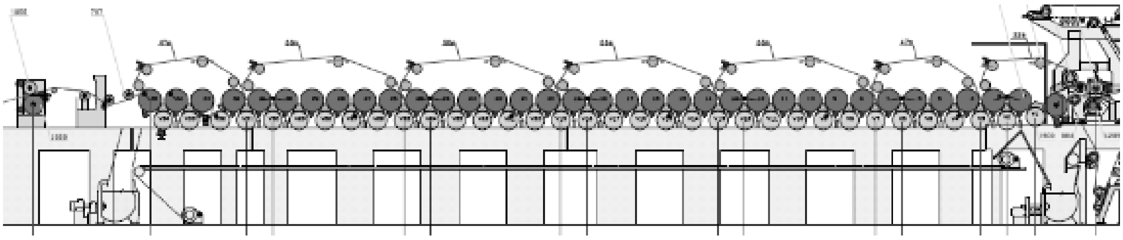

Figure 3. Multicylinder dryer example.[3]

Air impingement drying: A method of drying paper by blowing hot air onto the web surface, which increases the heat and mass transfer rates and reduces the drying time and energy consumption. An example of an impingement dryer is shown in Figure 4.

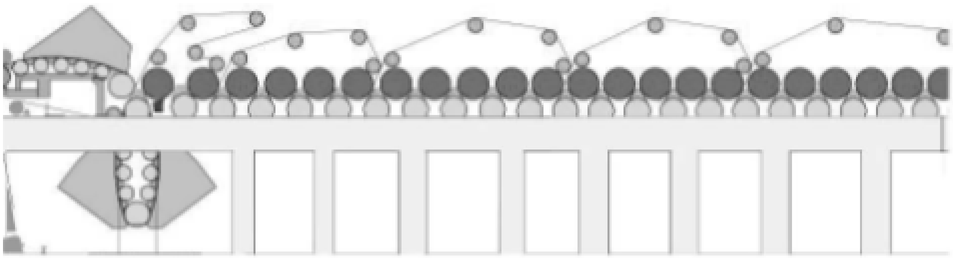

Figure 4. Impingement dryers at the beginning of the dryer section of a papermachine.[4]

Drying of paperboard and packaging grades: A category of paper drying that involves higher basis weights, lower porosities, and higher strength requirements of the paper

[2] https://bioresources.cnr.ncsu.edu/wp-content/uploads/2020/03/2001.1.709.pdf
[3] Fapet, Volume 9 - Papermaking Part 2, Drying. ISBN 978-952-5216-37-0, p. 82
[4] Fapet, Volume 9 - Papermaking Part 2, Drying. ISBN 978-952-5216-37-0, p. 87

products, which can be met by using multi-cylinder dryers, air impingement dryers, or infrared dryers.

Drying of tissue: A case of paper drying that requires high softness and bulk of the product, which can be achieved by using through-air drying (TAD, Figure 5), Yankee drying (Figure 6), or hybrid drying systems.

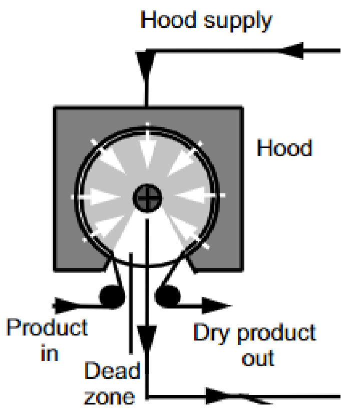

Figure 5. Through-air drying process (TAD).[5]

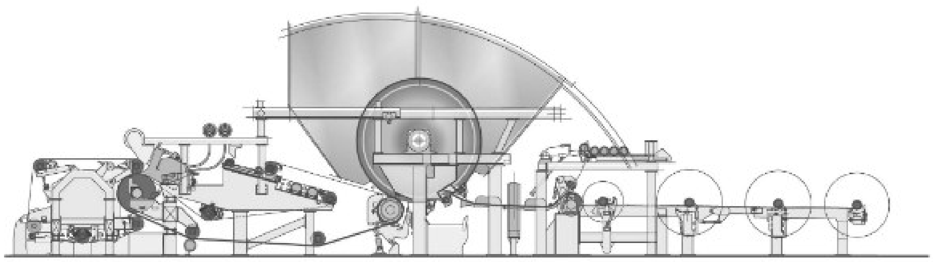

Figure 6. Yankee-dryer[6].

2.2 Drying of nonwovens

Nonwoven is a web having a structure of individual fibers that are randomly interlaid, but not in an identifiable manner as in a knitted fabric.[7] Nonwoven web formation can be done with dry-laid, airlaid, wetlaid, spunlaid, meltblown or submicron spinning. In drylaid forming, fibers are laid down in a dry state to form a web. The fibers can be arranged using methods like carding or airlaying. This technique is versatile and commonly used for producing a wide range of nonwoven fabrics, including those used in hygiene products, wipes, and insulation. Wetlaid nonwovens involve suspending fibers in water to create a slurry, which is then deposited onto a screen to form a web. The water is drained away, leaving behind a bonded fiber web. Wetlaid nonwovens are often used for applications requiring high uniformity and strength, such as filtration media and speciality papers.

The Bonding mechanism in nonwovens can be thermal, mechanical or chemical. In thermal bonding, calendering or through air heating methods are used. In mechanical

[5] Fapet, Volume 9 – Papermaking Part 2, Drying. ISBN 978-952-5216-37-0, p. 199
[6] Fapet, Volume 9 – Papermaking Part 2, Drying. ISBN 978-952-5216-37-0, p 165
[7] https://doi.org/10.1016/B978-0-323-26698-7.00011-8

bonding, needle punching, hydroentanglement or stichbonding are methods available. In finishing treatments mechanical, surface modifications or coatings are used.[8] For wetlaid nonwovens, drying plays a significant role in energy consumption[9]. Heat transfer methods are conduction in calendaring or drum drying, convection in through-air, impingement, flotation or belt-type dryers and radiation in microwave or Infrared dryers. The dryer type is selected based on the properties of the wet nonwoven, bonding agent, the desired properties of the finished product and production speed.[9, 10]

2.3 Drying of wood

In Europe, 109 Million m^3 of sawnwood was produced in 2020.[11] This equals about 55 Mt (dry matter).[12] To speed up the drying of wood material and to achieve desired end properties oven, kiln, bundle or rotary drum dryers have been increasingly popular.[32] They can use natural gas or electricity as an energy source. Heat is transferred into wood via convection (Figure 7). Also vacuum dryers, that remove water under partial atmospheric pressure, are used. Convective dryers are divided into low and high temperature dryers and vacuum dryers into conductive, superheated steam and dielectric dryers. In conductive vacuum drying (CVD), wood stacks are laying on electrically heated metal plates, improving heat transfer conductively, while they are inside the vacuum chamber. Dielectric vacuum drying (DVD) is similar than CVD but instead of heated metal plates, in DVD, drying is assisted radiatively with electromagnetic waves of different frequencies. Superheated steam vacuum drying (SSV) utilizes superheated steam that is forced convectively through the wood that is stacked in a chamber.[13] A list of typical industrial dryers for wood and their scale is shown in Table 2.

[8] https://www.edana.org/nw-related-industry/how-are-nonwovens-made
[9] Energy Savings In Thermal Nonwovens Processes | Textile World
[10] https://www.sciencedirect.com/book/9780128189122/handbook-of-nonwovens
[11] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Wood_products_-_production_and_trade#Primary_wood_products
[12] https://openknowledge.fao.org/server/api/core/bitstreams/eebaeee6-cd98-4b35-9143-21f96fad16af/content
[13] Springer Handbook of Wood Science and Technology | SpringerLink

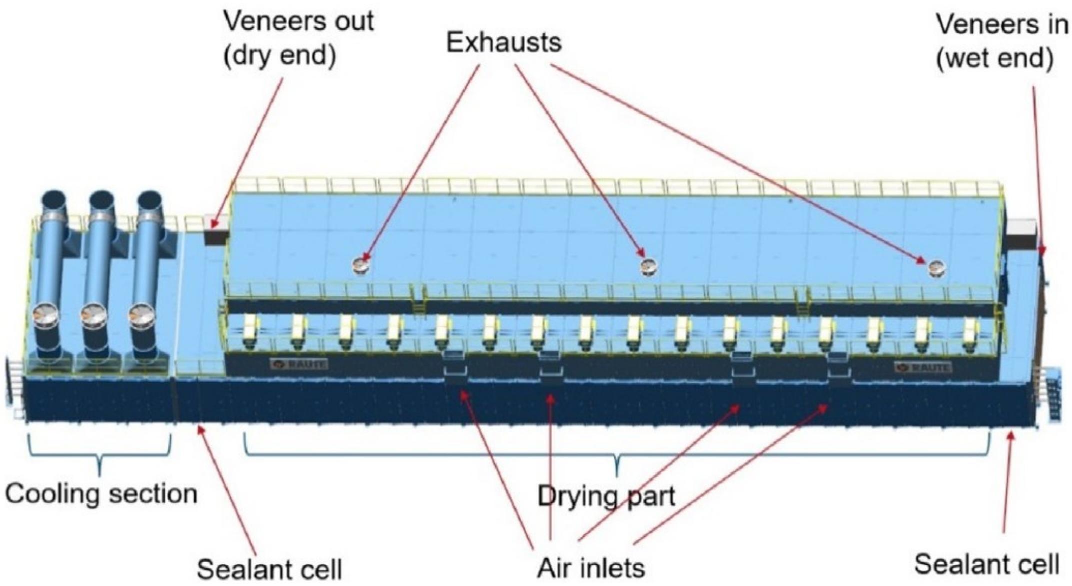

Figure 7. Illustration of the veneer drying unit.[14]

Main wood materials from sawnwood are: wood-based panels, veneer sheets, plywood, particle board, fibreboard, hardboard, oriented strandboard, medium/high density fibreboard (MDF/HDF) and other fibreboard.[15] In veneer production, thin layers of wood are peeled or sliced from logs. The logs are softened by soaking or steaming before being fed into a veneer lathe or slicer. Sliced veneer sheets are then dried in a roller dryer passing through it in several levels and blowing hot air from the jet boxes onto veneer surfaces. Duration of drying is few minutes in temperatures close to 200 °C.[13, 33] From veneer, plywood is made, where multiple veneer sheets are glued together at right angles to each other. The sheets are pressed and heated to cure the adhesive. In particle board manufacturing, wood chips, sawdust, and other small wood particles are mixed with resin and pressed into sheets. The mixture is then heated to cure the resin. Fibreboards of different densities start with separation of wood fibers, that are broken down from wood chips or other wood waste. The fibers are mixed with resin and pressed into sheets. MDF (Medium Density Fibreboard) and HDF (High Density Fibreboard) differ mainly in their density and strength. In hardboards, the density can be even higher and also steam and pressure is used. OSB is made from large wood strands that are oriented in specific directions and bonded together with resin. The strands are layered and pressed to form a strong, rigid panel[16].

[14] Gradov et al., Modelling of a continuous veneer drying unit of industrial scale and model-based ANOVA of the energy efficiency, Energy, Volume 244, Part A,2022,122673,ISSN 0360-5442, https://doi.org/10.1016/j.energy.2021.122673.
[15] https://ec.europa.eu/eurostat/databrowser/view/for_swpan/default/table?lang=en
[16] Production process of wood-based panels (processing-wood.com)

3 Energy consumption of dryers

3.1 Paper and board dryers in Europe

Paper and board mills have different specific energy consumption levels that are dependent on the end product[17] (Table 3). The BAT Reference Document is a comprehensive document that presents the results of an exchange of information between EU Member States, industries, non-governmental organizations promoting environmental protection, and the European Commission. The purpose of this exchange is to draw up, review, and update BAT reference documents as required by Article 13(1) of the Directive 2010/75/EU on industrial emissions. The BREF for the production of pulp, paper, and board covers activities such as the integrated and non-integrated production in industrial installations of: 1) Pulp from timber or other fibrous materials. 2) Paper or cardboard with a production capacity exceeding 20 tonnes per day. These documents ensure that industries adopt the best available techniques to minimise their environmental impact. They provide detailed guidelines and benchmarks for various industrial processes, helping companies comply with environmental regulations and improve their sustainability practices.

Table 3. Specific energy consumption directly used in the manufacturing process and the production-related ancillary installations of some example pulp and paper mills as given in table 2.9 in BAT/BREF-documentation of the European Bureau for Research on Industrial Transformation and Emissions[17].

Type of pulp/paper produced	Range of energy consumed	
	Units	from - to
Non-integrated kraft pulp	Power (kWh(ADt) Heat (kWh/ADt)	700-800 3800-5100
Integrated uncoated wood-containing paper (includes mech. pulping (MP) and may refer to GW, TMP or other types of fibres)	Power (kWh/t) Heat (kWh/t)	1200-1400 1000-1600
Integrated coated wood-containing paper (includes mech. pulping (MP) and may refer to GW, TMP or other types of fibres)	Power (kWh/t) Heat (kWh/t)	1200-2100 1300-1800
Integrated TMP-based printing paper (>90% TMP)	Power (kWh/t) Heat (kWh/t)	2500-2700 330
Non-integrated coated wood-free paper	Power (kWh/t) Heat (kWh/t)	600-1000 1200-2100
RCF without deinking (packaging) paper	Power (kWh/t) Heat (kWh/t)	300-700 1100-1800
RCF with deinking (graphic) paper	Power (kWh/t) Heat (kWh/t)	900-1400 1000-1600
RCF-based cartonboard (with deinking)	Power (kWh/t) Heat (kWh/t)	400-700 1000-2700

[17] https://eippcb.jrc.ec.europa.eu/reference/production-pulp-paper-and-board

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Type of pulp/paper produced	Range of energy consumed	
	Units	from - to
Non-integrated tissue mill (no TAD use)	Power (kWh/t) Heat (kWh/t)	900-1200 1900-2300
RCF-based tissue mill (no TAD use)	Power (kWh/t) Heat (kWh/t)	800-2000 1900-2800
Wood-free speciality paper	Power (kWh/t) Heat (kWh/t)	600-3000 1600-4500

The paper industry dryer types' energy consumption levels per ton of paper produced are around 1070 kWh/t for cylinder drying, 1100 kWh/t for Yankee, 1800 kWh/t for infrared, 1100 kWh/t for impingement and 1100 kWh/t for through air drying (TAD)[19].

Steam is mainly used in drying and it is the major component of mill total energy use (Figure 8). As seen in Figure 8, share between electricity use and steam use in e.g. packaging is 2 GJ/t of electricity and 7 GJ/t steam. Of the thermal energy costs it can be 80%, if also supply air heating is considered[18], [19].

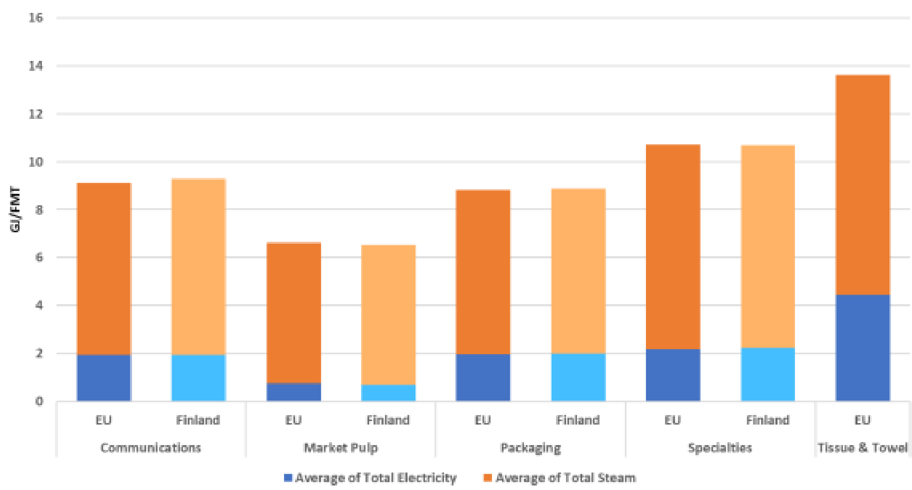

Figure 8. Total energy use in the EU and Finland by major grade 2019[20].

An estimate of current EU mills and their energy consumption levels are in the following table (Table 4).

[18] https://www.valmet.com/insights/articles/up-and-running/performance/XTControl/
[19] https://bioresources.cnr.ncsu.edu/wp-content/uploads/2020/03/2001.1.709.pdf
[20] https://www.motiva.fi/files/16820/Energy_Efficiency_of_Finnish_Pulp_and_Paper_Sector.pdf

*Table 4. Estimate of the current number of papermaking dryers and their heat/steam and electricity consumption levels***Error! Bookmark not defined., Error! Bookmark not defined., Error! Bookmark not defined., Error! Bookmark not defined.,** *TEREF _Ref178248627 \h* **Error! Bookmark not defined., Error! Bookmark not defined., Error! Bookmark not defined., Error! Bookmark not defined.,**

	Estimated No. of installations in 2023	Heat consumption (GJ/t), mill	Heat consumption (GJ/t), drying	Electricity (GJ/t) ADD	Average production, (kt)	Total thermal energy consumption (GJ/t)	Total production in EU, (Mt)	Total drying-related thermal energy consumption, PJ	Thermal average power in a mill, (MW)
Newsprint	10.0	4.4	3.7	2.0	344.0	8.0	3.4	12.9	48.1
Uncoated mechanical	17.0	5.5	4.7	2.0	228.0	8.0	3.9	18.1	39.7
Coated mechanical	11.0	5.1	4.3	2.0	325.0	8.1	3.6	15.5	52.5
Uncoated woodfree	62.0	6.5	5.5	2.0	118.0	12.4	7.3	40.2	24.2
Coated woodfree	20.0	6.6	5.6	2.0	193.0	14.5	3.9	21.7	40.5
Tissue	199.0	5.5	4.7	4.2	38.0	8.5	7.6	35.7	6.7
TAD	9.0	9.3	7.9	4.2	38.0	22.0	0.3	2.7	11.1
Kraftliner	36.0	5.9	5.0	2.0	92.0	4.9	3.3	16.5	17.2
Testliner	166.0	5.3	4.5	2.0	92.0	10.1	15.2	68.6	15.4
Fluting	153.0	5.0	4.3	2.0	92.0	10.1	14.0	59.6	14.6
Cartonboard	106.0	4.9	4.2	2.0	90.0	8.8	9.6	39.9	14.0
Other packaging grades	117.0	9.0	7.7	2.0	40.0	13.3	4.6	35.5	11.3
Other paper grades	134.0	9.0	7.7	2.0	29.0	13.3	3.9	29.9	8.3
Total	**1 040.0**						**80.6**	**396.8**	

3.1.1 Energy consumption in papermaking in Europe

Figure 9 illustrates the final energy usage in the papermaking industry in the EU. When comparing Table 4's drying-related energy consumption (~400 PJ, total of drying-related energy consumption is shown in the table) to Europe's total energy consumption (650 PJ) for the manufacturing of paper and paper products, the share is 62%. It demonstrates that energy consumption linked to drying, when examined across various statistical sources, is at least 62% and can approach 80% at the mill level.

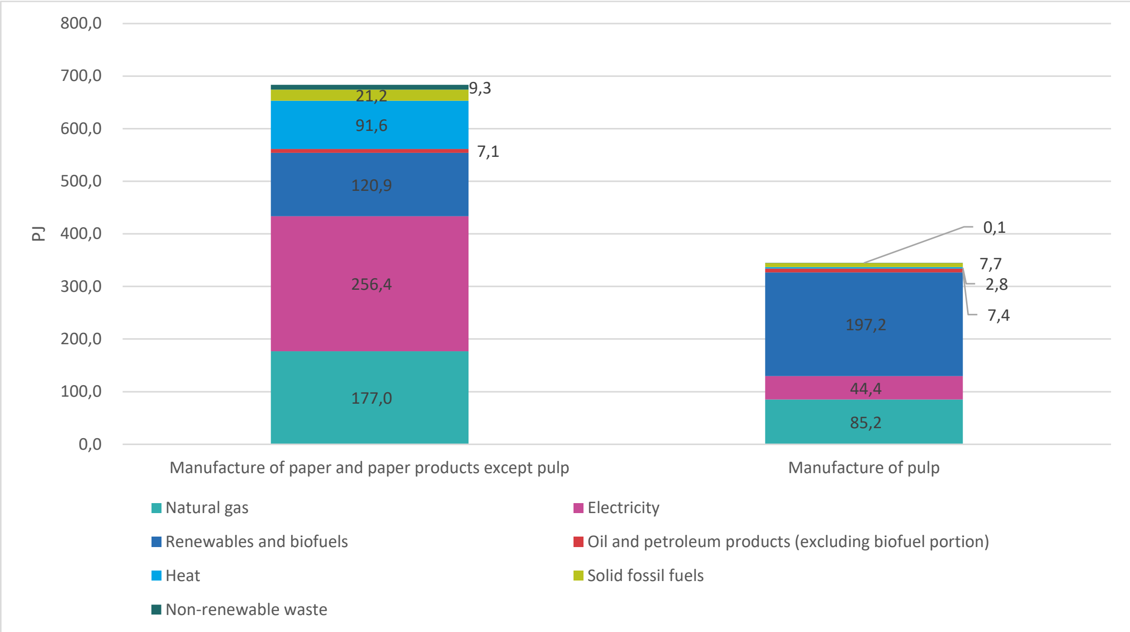

Figure 9. Final energy consumption (PJ) in the paper, pulp and printing industry by energy production technology, 2021.[21]

The source of energy data is Eurostat[21]. It shows that there is fossil fuel use, mainly from natural gas within paper manufacturing. These energy shares can be later used to assess CO_2 emissions and potential changes when SSD technology is applied. CO_2 emissions from the manufacturing of paper and paper products were 30,5 Mt_{CO2} in 2021, equalling 46.9 t_{CO2}/TJ. The industry relies to a large extent on renewables and biofuels for energy use, particularly in the manufacture of pulp (57% from renewables and biofuels), electricity has grown to be the largest energy component in manufacturing of paper and paper products (38% from electricity), followed by natural gas (26%).

Their estimated CO_2-emissions per energy source in 2021 are shown in Figure 10. In the figure average values are used, and e.g. electricity is not weighed based on actual pulp or paper production in each country and countries producing large share of European pulp and paper have typically a low CO_2 emission factor. This should be later estimated in more detail, as the share of electricity-related CO_2-emissions is large. The same applies also for heat. It should be noted that European electricity emission factor decreases fast[22].

[21] https://ec.europa.eu/eurostat/databrowser/view/nrg_d_indq_n/default/table?lang=en

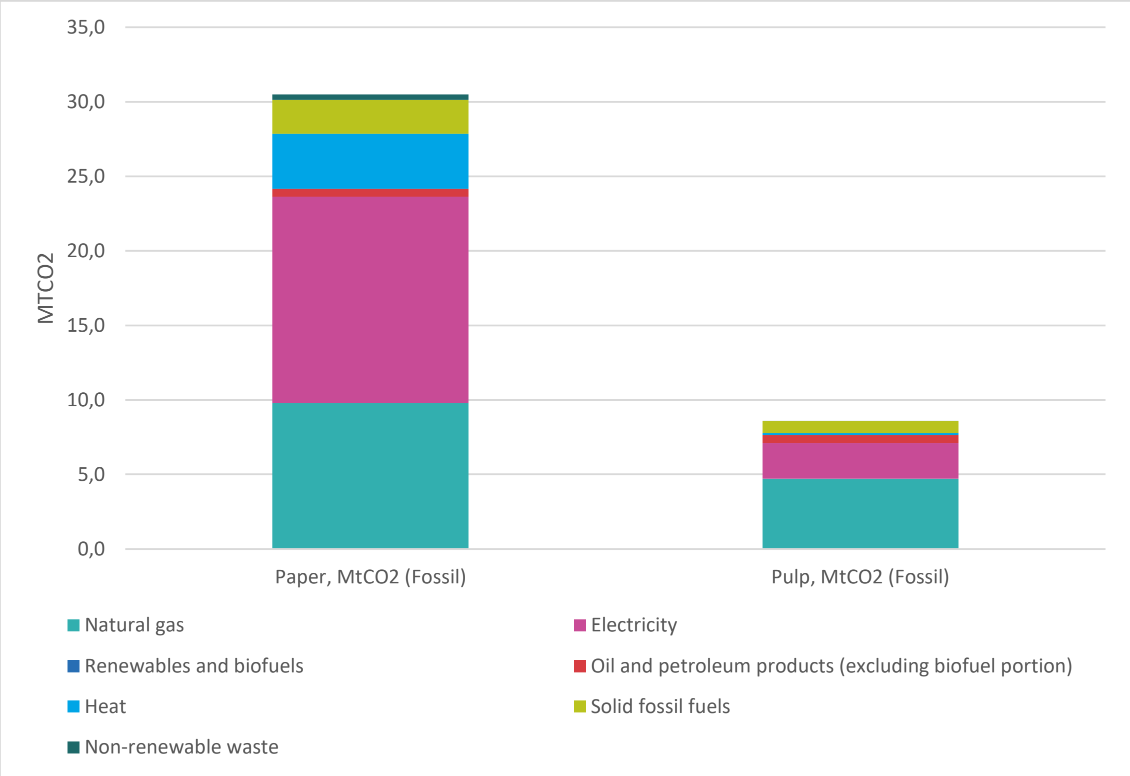

Figure 10. Estimated CO_2 emissions from Eurostat[21] in the pulp and paper manufacturing divided for each primary energy source using CO_2-emission factors[22], [23].

3.2 Nonwoven energy consumption in Europe

Nonwovens production in Europe was about 3 million tonnes in 2022[24]. Wetlaid nonwovens production was about 10% of this.[25] The energy consumption of modern production of nonwoven ranges from 1.3-2 MWh/t[26]. The energy consumption of wetlaid nonwovens in Europe is then 1.4-2.2 PJ. However, a larger variation is also reported between 0.9-6.5 MWh/t.[27] Nonwoven line capacity ranges from 10 000 – 100 000 t/a, line speeds are up to 500 m/min, width up to 5.5 m and basis weight from 12 – 400 g/m^2.[28]

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[22] Bastos, Joana; Monforti-Ferrario, Fabio; Melica, Giulia (2024): GHG Emission Factors for Electricity Consumption. European Commission, Joint Research Centre (JRC) [Dataset] PID: http://data.europa.eu/89h/919df040-0252-4e4e-ad82-c054896e1641

[23] https://www.motiva.fi/ratkaisut/energiankaytto_suomessa/co2-paastokertoimet

[24] https://www.edana.org/about-us/news/in-2023-european-nonwovens-production-decreased-by-5.7

[25] https://www.nonwovens-industry.com/issues/2020-04-01/view_features/the-future-of-wetlaid-nonwovens-to-2025/

[26] https://reifenhauser.com/en/company/media/news-and-stories/success-story/carbon-footprint-reduction-in-nonwoven-production

[27] *Kır, A., Ozturk, E., Yetis, U. et al.* Resource utilization in the sub-sectors of the textile industry: opportunities for sustainability. Environ Sci Pollut Res 31, 25312–25328 (2024). https://doi.org/10.1007/s11356-024-32768-2

[28] https://www.andritz.com/resource/blob/67086/c8814be399b239e887ed565d50a6941e/brochure-wetlaid-line-solutions-2019-data.pdf

3.3 Wood material drying energy consumption in Europe

According to FAOSTAT[29], the production in Europe in 2022- was 9.2 Million m³ (Table 5).

Table 5. Wood-based panels production in Europe in 2022.

Product	2022 production in Europe, m³	Share
Veneer sheets	3 300 217	4 %
Plywood	8 419 354	9 %
Particle board	44 820 326	49 %
OSB	9 550 353	10 %
Hardboard	1 966 325	2 %
MDF/HDF	20 003 246	22 %
Other fibreboard	3 981 231	4 %

E.g. in Veneer manufacture plywood drying consumes 70% of total energy consumption.[30] Veneer can contain 1-2 kg_{H2O}/kg(dry matter), which is close to the original moisture of wood after harvest, the amount to be dried in wood materials can be 55-110 Mt annually in Europe. Modern veneer drying machine consumes about 400 kWh/m³ (dry veneer), 0.8 MWh/t of wood. Modern veneer dryer has increased to stacking speed of 300 m/min, with eight dryer decks and 6,2 m width.[31] The dryer capacity can be adjusted with modules that increase length of dryer, depending on capacity needs.

Particle board consumes heat 0.2-1.7 MWh/m³, OSB 0.1-0.7 MWh/m³ and MDF 0.3-2.9 MWh/m³.[32] Panels in Europe have a median density of 600 kg/m³, [12] then average heat uses are for particle board 1 MWh/t, OSB 0.7 MWh/t and MDF 2.7 MWh/m³.

By weighing the production shares in Europe, the average heat requirement is 1.3 MWh/t. Then the heat requirement for drying is 70-140 PJ.

3.4 Heat integration options in the current dryer

Currently, air is used in dryers in the paper industry to remove moisture. Figure 11 shows an example of the energy flows for a newsprint paper machine. The exhaust humid air leaving the dryer is often used to preheat the supply air in a heat exchanger, (Figure 11), yet losses occur. If water is condensed out of the exhaust humid air, a large amount of energy can be recovered.

[29] https://www.fao.org/faostat/en/#data/FO
[30] https://doi.org/10.1016/j.energy.2021.122673
[31] https://www.grenzebach.com/en/company/news-press/detail/quality-and-energy-efficiency-in-veneer-drying/
[32] https://eippcb.jrc.ec.europa.eu/sites/default/files/2019-11/WBPbref2016_0.pdf

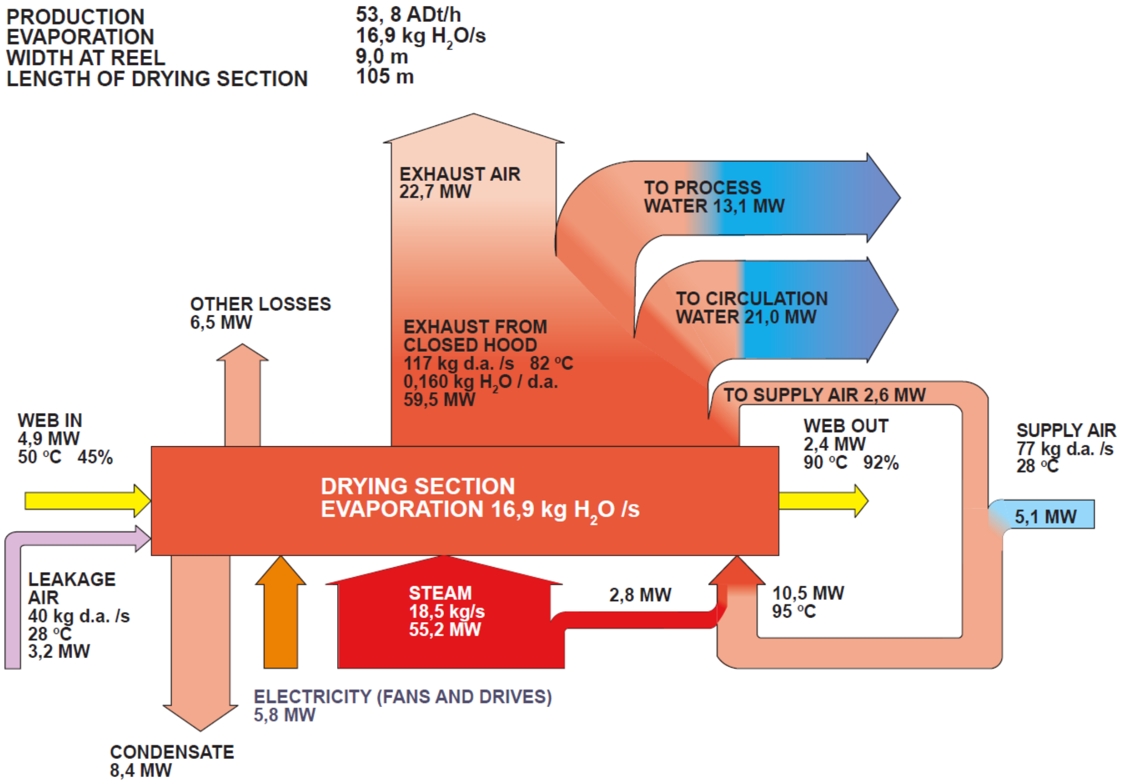

Figure 11. Energy flows of newsprint paper machine dryer section[33].

Figure 12**Error! Reference source not found.** shows how much energy can be recovered from 1 t/h of humid exhaust air with an initial temperature of 90°C and a relative humidity of approx. 17% as a function of the temperature to which the exhaust air is cooled (final temperature in Figure 12). The dew point is approx. 49°C and it is the transition from the linear to curved section in Figure 12.

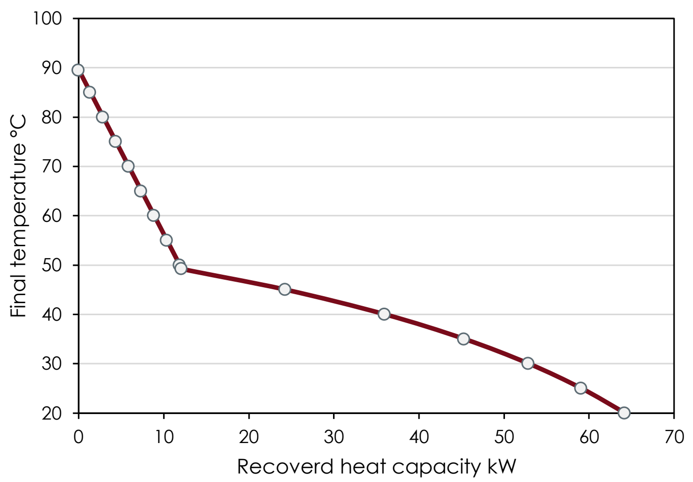

Figure 12. Recoverable heat capacity from humid exhaust air as a function of the temperature to which the exhaust air is cooled (Final temperature).

33 https://forestbiofacts.com/

To illustrate the energy saving potential of two heat integration options using a conductive dryer, parameters of a paper machine at the plant in Pitten of W. Hamburger GmbH operated with steam-heated cylinders from the studies by Schneeberger[34] were used as a basis. For this purpose, models created in the IPSEpro tool were applied. The tool is explained in more detail in Chapter 4.3. For the investigations, the dry content of the paper and thus its sensible heating was neglected. The assumptions for calculating the dryer without heat recovery and the results incl. energy demand of approx. 17 MW are shown in Figure 13**Error! Reference source not found.**. In this variant, the thermal energy required for drying is provided exclusively by the steam-heated drying cylinders, with the steam often being generated by natural gas-fired steam boilers.

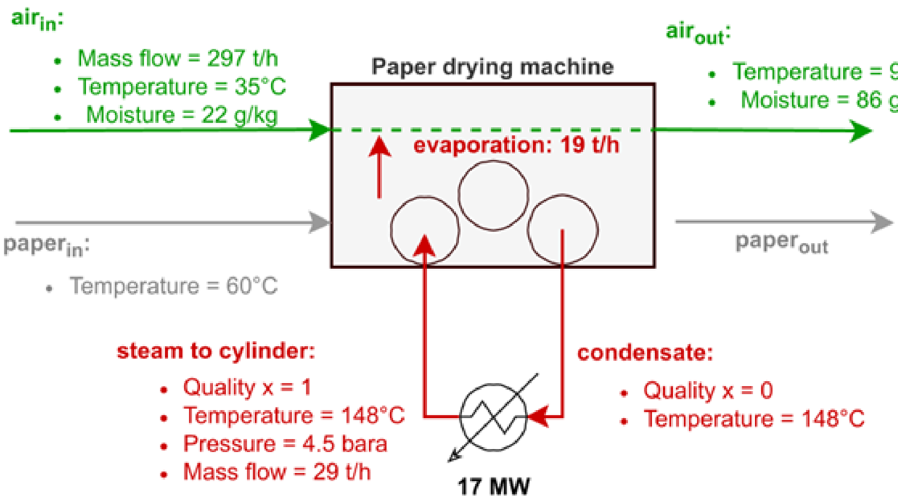

Figure 13. Assumptions and results incl. energy demand for a conductive dryer without heat recovery based on Schneeberger[34].

A method for heat integration is shown in Figure 14, including the assumptions and the results incl. the energy demand and the recovered heating capacity of approx. 3 MW. This variant uses an air-to-air heat exchanger to heat the incoming air flow to the dryer with the exhaust humid air. Due to the elevated inlet air temperature, the energy demand is reduced (approx. 17%).

[34] *Schneeberger, M.* "Energetische Trocknungsoptimierung bei Papiermaschinen mittels Simulation der Stoff- und Wärmeübertragung unter Berücksichtigung der trocknungsrelevanten Eigenschaften der Faserstoffe", Dissertation, 2014, DOI:10.3217/wemj3-gq226

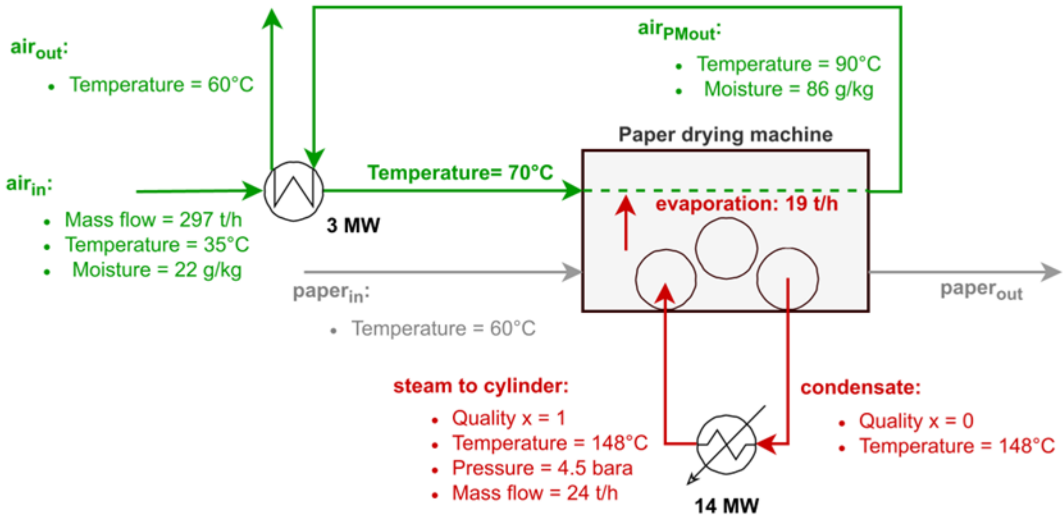

Figure 14. Assumptions and results incl. thermal energy demand for a conductive dryer with a heat exchanger for heat recovery of energy from the humid exhaust air and preheating of the dryer inlet air.

The heat integration option shown in Figure 15 uses a heat pump in addition to a heat exchanger to provide the total steam demand of the drying cylinders. The exhaust humid air stream is used as a heat source for the heat pump, after it has been used to preheat the drying inlet air with a heat exchanger. Moreover, a water intermediate cycle with a counterflow heat exchanger was considered between the exhaust humid air stream and the source side of the heat pump. For calculating the heating capacity and the energy demand of the heat pump a second law efficiency of 0.5 was assumed. The second law efficiency describes the deviation of the real heat pump process from the ideal reference process. Due to the energy efficient working principle of heat pumps, the energy demand of approx. 14 MW as shown in Figure 14 can be significantly reduced in this option. The electrical energy demand of the heat pump is approx. 8 MW. This results in a 55% reduction in energy demand compared to the case without heat recovery.

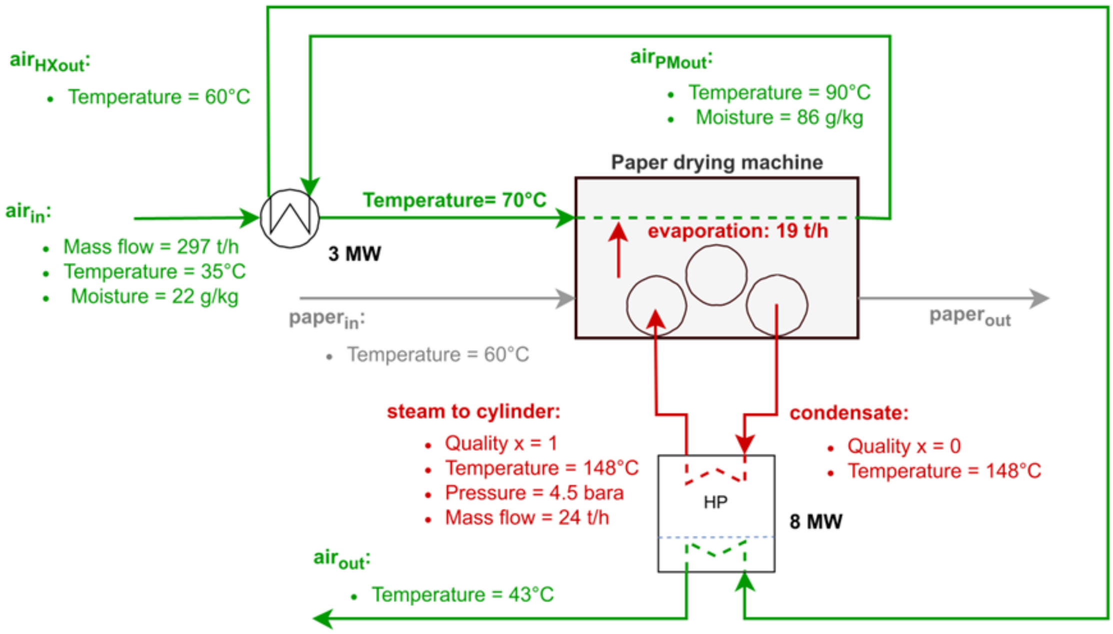

Figure 15. Assumptions and results incl. energy demand for a conductive dryer with heat exchanger and heat pump for heat recovery of energy from the humid exhaust air to preheat the dryer inlet air and to provide the steam for the drying cylinders.

In the case of convective drying paper machines, e.g. impingement dryers, the necessary heat for drying the paper and the needed moisture absorption capacity is provided exclusively by hot air. In this case, too, heat recovery with a heat exchanger and/or heat pump technology is possible, whereby the recovered energy is supplied exclusively to the dryer supply air. As the air temperature for convection dryers is very high (> 250°C), the application of an additional heating technology will be necessary.

At present, an increasing number of high-temperature heat pump technologies that provide supply temperatures above 100°C are available on the market or are under development [35]. For example, closed loop vapor compression heat pumps that operate in the subcritical range of the refrigerant or closed loop heat pumps based on the Stirling process are feasible candidates.

Another high-temperature heat pump technology is the steam compressor. Steam compressors can be used to increase the pressure and temperature of an existing steam mass flow. During compression, the steam mass flow generally superheats. The degree of superheat can be controlled by water injection. The water injection is used to keep the steam temperature below the design temperature of the equipment and increases the efficiency of the compression process. The injected water evaporates along the compression path and the steam mass flow increases towards the outlet of the compression system.

Various compressor types can be used as steam compressors, such as turbo compressors – usually for large capacity systems – or piston or screw compressors for small capacities. Piller Blowers & Compressors GmbH, for example, is a manufacturer of turbo compressors.

[35] Heat Pump Centre Ed., IEA HPT Annex 58 High-Temperature Heat Pumps. Task 1 - Technologies, Task Report, August 2023, Schweden, ISBN 978-91-89821-34-7, https://heatpumpingtechnologies.org/annex58/task1/, Accessed on 11.09.2024.

Different system configurations can be used in combination with steam compressors. One option is to use them in combination with heat exchangers, where the water is either evaporated directly or heated up using waste heat. If the water in the heat exchanger is only heated up and not evaporated, a flash tank can be used to generate steam. Figure 16 describes the humid exhaust air from a paper machine when it is used in a heat exchanger to produce hot water. Low pressure steam is first generated in a flash tank and then further compressed by the steam compression system to target pressure, where it can be used for heating at the paper machine and other processes.

However, steam compressors can also be used in combination with closed loop heat pumps to increase the pressure and temperature of the steam generated by the closed loop heat pump.

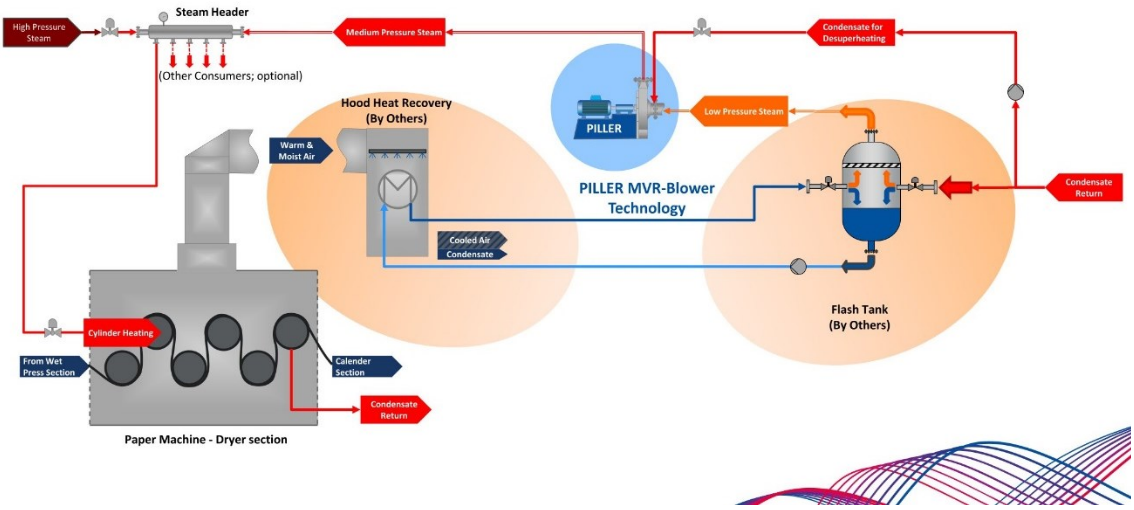

Figure 16. Steam compressor in combination with heat exchanger and flash tank for steam generation using heat recovery from the exhaust air of a paper machine (Author: Piller Blowers & Compressors GmbH).

3.5 Research status today

Intensive drying technologies studied during the previous 25 years are a group of emerging paper drying methods that use different forms of energy to achieve higher drying rates and better paper quality. These are impulse drying, Condebelt drying, direct steam drying, infrared drying, and microwave drying or some combinations of them. In this project the development possibility selected was superheated steam drying (SSD) which is presented briefly in the next chapter.

4 Superheated steam drying

4.1 Principle

When water is heated at a specific pressure, it forms saturated steam at its boiling point, and by further heating of saturated steam above the boiling point at a corresponding pressure, the saturated steam is converted into superheated steam.

The utilisation of heated steam beyond its boiling point as a drying medium in a dryer to remove excess water from the material is known as superheated steam drying (SSD).

Saturated steam is condensed as soon as there is a drop in temperature, but no condensation occurs in superheated steam if temperature is maintained above saturation temperature at a specific pressure.

The evaporated vapor from the product becomes part of superheated steam, which can be removed and readily condensed to provide heat for other applications, saving the cost of energy, and superheated steam can be recycled. This results in low net energy consumption and utilization possibility of exhaust steam.

4.2 Main foreseen process changes to the current dryer

According to literature[36], [37], [38], at least the following issues and considerations should be taken into account: Start-up and shut-down; air infiltration especially sealing of the hoods at high speeds; materials of construction especially corrosion/erosion; steam cleaning, re-circulation, compression, re-heating, etc; fouling of heat exchanger surfaces; and coupling of steam dryers with conventional dryers, if necessary and quality aspects of paper.

As long as steam remains superheated, it can be used for power generation or reused in drying. The main difference to existing dryers in papermaking is that there is no hot air, which limits the energy utilisation.

4.3 Investigations on SSD concepts using models

The paper drying process, as well as the integration of heat recovery equipment, were investigated using the simulation software IPSEpro (Integrated Process Simulation Environment), which was developed for process simulations in the field of power plant and energy technology. The setup implemented as a flowsheet in IPSEpro corresponds to the actual process layout. The individual components of the process (unit operations such as the dryer, compressors, heat exchangers, etc.) are connected by streams that transfer mass and energy. The components are balanced according to conservation of mass and energy and the balances are strictly fulfilled for each component.[39]

4.3.1 Concept for conductive cylinder dryers

An SSD concept evaluation for evaporating 1 t/h of water from paper was already made and presented for conductive cylinder dryers-case in an article[39].

[36] *Kiiskinen, H. and Edelmann, K.* Superheated Steam Drying of Paper Web (2002) Developments in Chemical Engineering and Mineral Processing - Wiley Online Library
[37] Kadant Inc. - Saturated, Wet, and Superheated Steam in Paper Drying
[38] Drying with superheated steam at atmospheric pressure - Fraunhofer IGB
[39] https://www.proceedings.com/content/069/069564-0128open.pdf

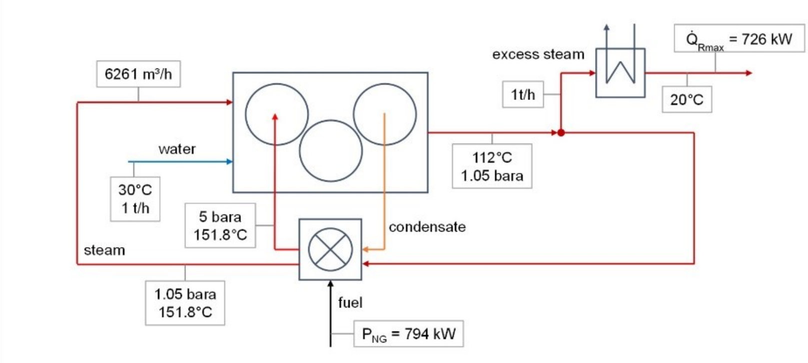

Figure 17. Superheated steam drying with drying cylinders[39].

In the article, the medium of the dryer atmosphere is changed from air to superheated steam with 151.8°C (Figure 17). Regarding the pressure, a slightly higher value (1.05 bar_a) than atmospheric pressure was assumed to avoid air intake. For the steam volume flow 6261 m³/h was assumed. This volume flow is the same as in the case where air is used in the atmosphere of the dryer, which was also analysed in the article.

Slightly superheated steam (10 K) with a temperature of 111°C was assumed at the dryer outlet. This assumption is to ensure that no condensation occurs while paper drying. To ensure the mass balance, some of the outlet steam must be removed (excess steam), while the rest of the steam can be reheated (e.g. natural gas boiler) to the inlet temperature and can be used in the dryer again.

Moreover, in the presented concept steam cylinders are supplied with saturated steam at 5 bar_a and 151.8°C, independently of the stem in the atmosphere. The stream condenses due to heat transfer for drying in the cylinders. The condensate can then be evaporated again by adding heat capacity (e.g. natural gas boiler) and reused. If natural gas boilers (thermal efficiency 90%) are used to supply the dryer, the natural gas demand is 794 kW. If the excess steam mass flow is cooled to 20°C, a heat capacity maximum of 726 kW is available for further use. A large share of heat recovery potential is caused by condensation of the excess steam mass flow (at a condensation temperature of approx. 101°C).

4.3.2 Concept for convective impingement and TAD-dryers

In convective dryers, the energy required for drying is provided exclusively through direct contact between the paper and the drying air. This drying air can also be replaced by superheated steam. To provide a certain amount of energy for drying there is generally a correlation between temperature and mass flow. Figure 18 shows this correlation for the drying of 55 t/h of water using superheated steam. A simplified model in IPSEpro was used for the calculation. When the steam temperature increases then steam mass flow can be decreased as higher temperature steam contains more energy.

In general, lower steam temperatures are advantageous for the application of heat recovery technologies and on the other hand, the higher the temperature, the higher the drying rate and the more compact the dryer, see Figure 19.

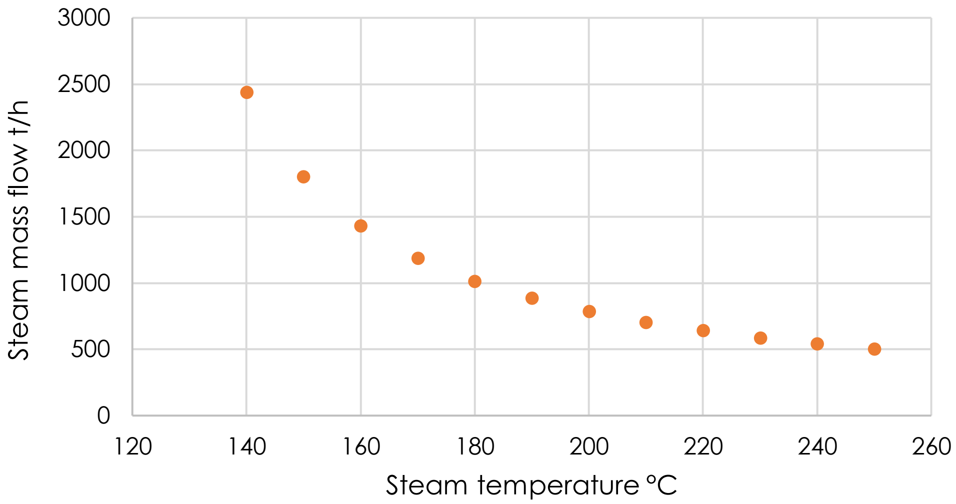

Figure 18. Correlation between steam temperature and mass flow for drying of 55 t/h water.

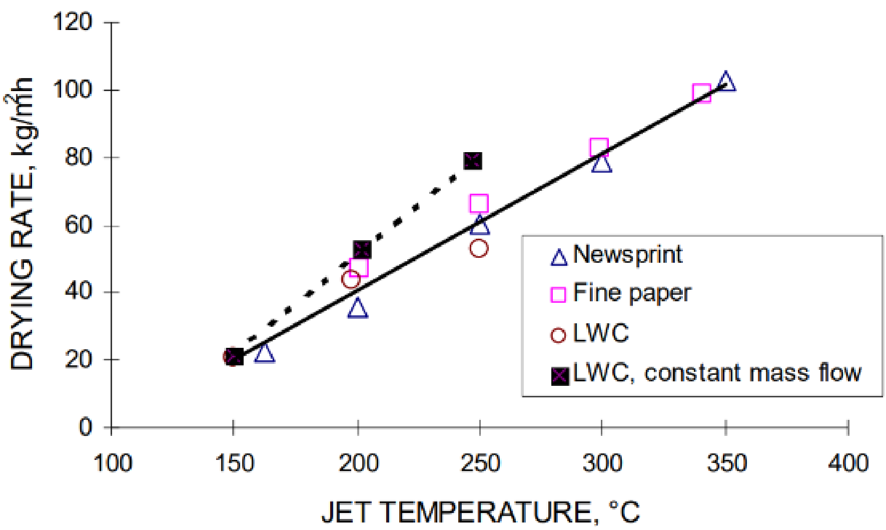

Figure 19 Drying rate vs. steam temperature in impingement drying[36]

5 Vision roadmap

In this deliverable, we have so far introduced the drying technologies for web-like materials, the energy consumption of dryers, and the option of superheated steam drying. Based on these observations, the SteamDry consortium has drafted a vision roadmap for the SSD transition. The goal of this roadmap was to align a view of the possible technology adaptation timeline at the time of its creation and its potential to change energy requirements for existing technology. The stakeholders of the vision roadmap creation are project partners.

5.1 Roadmap creation phases

Project partners participated in the creation of the roadmap via discussions and workshops.

The aspects considered ranged from the challenges and technology development needs eventually to their study timelines.

First, partners created a challenge and open questions framework, as well as potential applications to focus on. These are summarised in Figure 20.

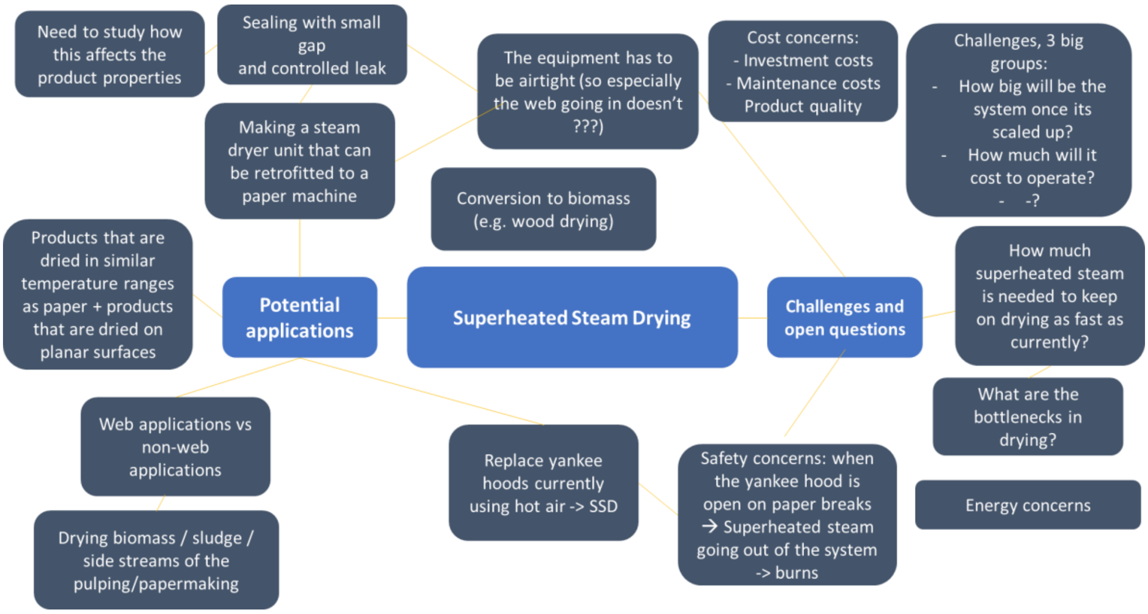

Figure 20. Superheated steam drying - Challenges and open questions with main potential application areas using project results.[40]

The project commercialisation vision identified which steps will be in between the SteamDry project and a commercial installation, and which problems we need to be solved in order to get there. In addition, there were attempts to estimate how much time is needed to solve the identified challenges. The methodology follows the principles of a Minimum Viable Product (MVP). An MVP is a product or service with just enough core features to be deployed to a select group of customers and early adopters. This allows for direct and valuable feedback while it's still early and inexpensive to make changes.

These technology-driven focus areas were then divided into following 5 groups with participants both from R&D and industry:

1. Dryer unit
2. Process around the dryer
3. Steam purification
4. Sealing the steam dryer
5. Product quality

These groups follow the development needs of the project, containing needed modelling actions inside.

[40] Valmet facilitated a workshop that resulted in this picture (SteamDry kick-off January 2024)

5.2 Roadmap

The consortium identified the main development steps towards to a commercial SSD dryer. The steps were processed by aforementioned five topic groups. Each group had some initial questions that they worked on.

The project has a timeline of 3.5 years and part of development steps can be performed within the project. Groups also estimated the efforts needed after the project. These were then aligned to create the roadmap. The selection of piloted cases will be done in early 2025.

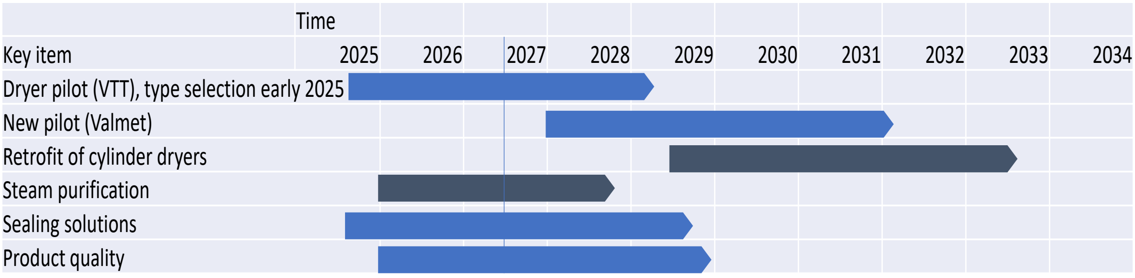

Figure 21. Key item timelines created during workshops.

The roadmap created is presented in Figure 22. It has been divided into pilot, demo and flagship -phases. Before the piloting phase, there is already an ongoing laboratory-phase. Laboratory-phase has been estimated to end already at the end of the project. During SteamDry-project laboratory studies, steam purification, sealing solutions and piloting at VTT are done with product quality estimations. After the project, to increase TRL, a more extensive demonstration phase in a larger pilot is likely required. For retrofit to existing machinery, a flagship is a logical continuation starting at the end of this decade.

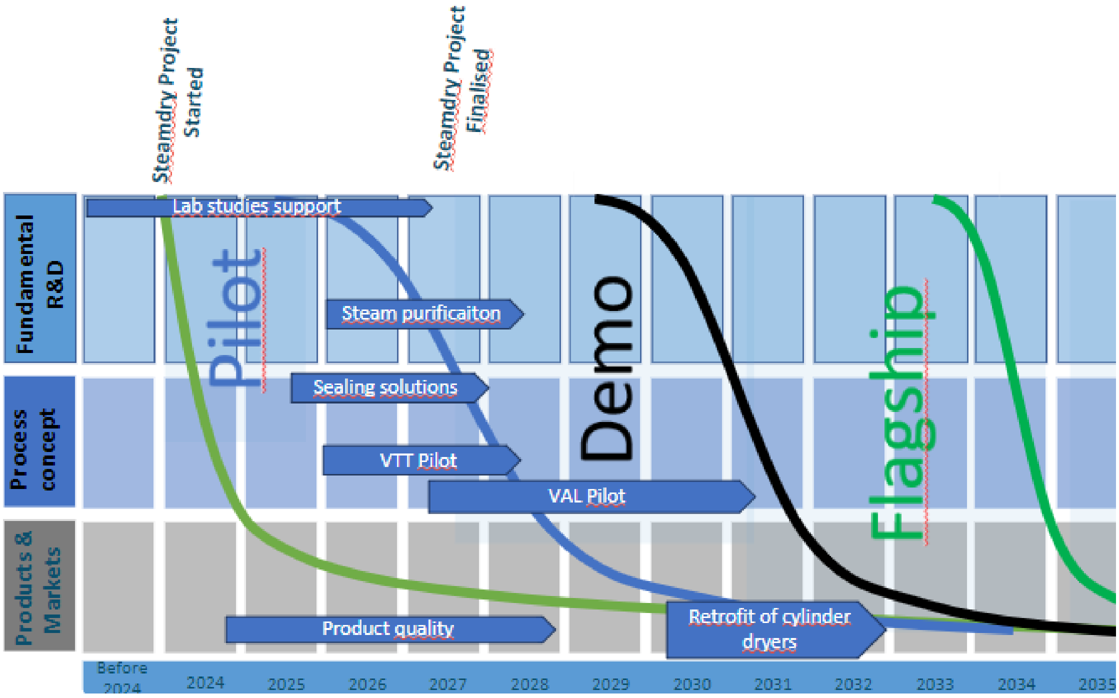

Figure 22. Vision of main steps towards superheated steam drying application in papermaking.

Elements presented in this roadmap have more detailed material developed for the use of consortium that is not shown in this deliverable. Roadmap represents ideas as they are seen in 09/2024. As there are changes in the work needed or the foreseen timeline, this roadmap will be updated as a new version.

6 Summary

The SteamDry project has several objectives, including developing energy-efficient drying technology, achieving a CO2-emission-free drying process, and piloting the SSD process for web-like products. The project also focuses on environmental and techno-economic assessments, evaluating the business potential for various product manufacturing sectors, and communicating, disseminating, and exploiting project outcomes.

This deliverable outlines the **vision roadmap** for the transition to superheated steam drying (SSD) technology, starting from 2024 onwards. The roadmap includes fundamental R&D, pilot, demo, and flagship phases leading to commercial operations. Key milestones involve developing a process concept, plant engineering, and market suitability.

SSD Technology: The SteamDry project aims to revolutionize drying processes in the pulp and paper, nonwoven, and wood material industries by introducing SSD technology. Traditional drying methods like contact cylinder and convective hot air drying have limited energy efficiency and inevitable CO2 emissions. In contrast, SSD technology leverages the superior heat transfer properties of superheated steam, circulating and reheating it in a closed loop. This results in lower net energy consumption and the use of surplus steam for other purposes within the facility, enhancing energy efficiency.

SSD technology offers several advantages over traditional methods, including faster drying rates, shorter drying times, minimized product degradation, and improved overall product quality. The compact design of SSD dryers and the ability to reuse surplus steam for other industrial processes further enhance energy efficiency and operational sustainability. The project emphasizes system integration and advanced digitalization of monitoring and control systems. Through pilot-scale measurements and comparisons with commercial best practices, the project aims to demonstrate the substantial improvement potential of its integrated approach to drying technology.

Roadmapping: The roadmap for SSD transition spans from 2024 onwards, starting with fundamental R&D and progressing through pilot, demo, and flagship phases leading to commercial operations. The roadmap's aim is to develop a process concept, plant engineering, and market suitability for SSD technology and identify the needed steps towards the goal. The creation of the roadmap involved collaboration between various project partners.