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Decarbonizing industrial process heat: the role of biomass

A report for the IEA Bioenergy Inter-task project on industrial process heat
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Decarbonizing industrial process heat: the role of biomass

By Olle Olsson[1] & Fabian Schipfer[2]

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[1]Stockholm Environment Institute

[2]Vienna University of Technology

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Summary

The industrial sector makes more than 30% of global CO_2 emissions. According to the International Energy Agency (IEA) “Net-Zero by 2050” scenario, industrial emissions have to decrease by more than 90% by 2050 in order for the world to have a 50% chance of limiting global warming to 1.5°C above pre-industrial levels. A substantial part of industrial emissions originates from the use of fossil fuels for the generation of process heat and hence, decarbonization of industrial process heat generation will be an essential component in eliminating industrial greenhouse gas emissions.

However, it is important to note that the umbrella term “industrial process heat” covers a broad range of different applications with many variations in terms of key characteristics pertaining to heat transfer and temperatures of operation. It can also be quite challenging to analyse and generalise issues around industrial process heat. This is not just because of the great heterogeneity under the heading, but also because the energy conversion and use both takes place within industrial facilities which means that there is not the same amount of transparency as in e.g., electricity markets.

Deep reductions in greenhouse gas emissions from the generation of industrial process heat can be achieved either by capture and permanent storage of CO_2 emissions (CCS) or by shifting to non-fossil means of generating heat, where the most promising alternatives of the latter include electrification, hydrogen and biomass. All these alternatives have pros and cons. CCS can allow for continued use of existing fossil fuel-burning equipment but is expensive and places high requirements on infrastructure for transport and storage of CO_2. Electrification can be quite promising for lower temperatures but for many high temperature applications, technologies are still at a rather early stage. Hydrogen is a promising solution to substitute natural gas-based heating and can play important roles as a chemical feedstock and a reduction agent in steel production, but substantial cost reductions are necessary for it to be competitive as a source of industrial process heat.

Bioenergy is currently the largest source of non-fossil industrial process heat, largely because of how forest industries utilize internally generated residues and by-products to e.g., dry timber in sawmills and produce process steam in pulp & paper mills. However, when it comes to broader opportunities of biomass for industrial process heat, it is key to understand that the substantial amount of heterogeneity that lies under the heading. Not only can biomass feedstock come in many different forms, there are also great many pathways by which the feedstock can be converted into process heat, including direct combustion but also by way of pre-processing approaches like torrefaction, gasification or liquefaction. These can be used to produce biomass-based fuels that are quite similar to the fossil fuels currently in use and hence, in principle, biomass can meet most industrial process heat needs. However, many of these pre-processing technologies are not commercially mature and costs of biomass vary greatly between locations which makes it difficult to make general statements about cost competitiveness of biomass as a source of industrial process heat.

Understanding of the opportunities in biomass-based approaches to provide industrial process requires thorough analysis not only of the technological demands of the process itself, but also of local feedstock availability and how appropriate fuel logistics systems can be set up. Close collaboration between different supply chain actors and long fuel supply contracts can often be key to provide the certainty needed to reduce investor risk. However, there are also key roles for policy makers to play, by helping to fund R&D as well as close-to-commercial demonstration facilities but also create demand e.g., through public procurement guidelines that incentivize low emission supply chains.

Contents

1 Introduction

1.1 INDUSTRIAL EMISSIONS – THE NEXT DECARBONIZATION FRONTIER

While projections based on current trends point to clear risk that the ambitions of the Paris agreement, of limiting climate change to well-below 2°C above pre-industrial levels, will not be realized, there are developments that could improve these prospects. For example, the share of wind & solar in the global electricity mix has doubled in the last five-year period and clean electricity is competing successfully against fossil fuels in a growing number of markets around the world (Jones et al. 2020). An increasing share of the global economy is also operating under commitments to reduce emissions to net-zero by mid-century. Notably, the fall of 2020 saw time-bound zero-emission commitments from three of the world's largest economies, with Japan and South Korea both aiming for 2050 and China for 2060 (McCurry 2020).

While the pathways for how these targets are to be met may remain unclear, one thing seems highly likely: these announcements will further strengthen the push towards decarbonization of not just electricity and ground transport, but of heavy transport and industrial processes as well. The latter have been referred to as the "hard-to-abate sectors", but there is increasing evidence that this may be somewhat of an exaggeration. A series of recent studies highlight that there are several technological pathways by which these could undergo zero-carbon transitions at relatively modest societal costs (Bataille et al. 2018; ETC 2018). This is encouraging but also absolutely necessary, in the light of how industrial emissions make up around 30% of global emissions of greenhouse gases.

1.2 THE CENTRAL ROLE OF HEAT

Our focus in this report is industrial process heat, but it is important to clarify already at this point that not all emissions generated from hot industrial processes originate from the heat generation as such, as there are substantial amounts of emissions that come as a result of the processes themselves. This is particularly important in the case of cement, where two-thirds of the CO_2 emissions are generated not from the combustion of fuels but come from the process of calcination, whereby quicklime is produced by separating CO_2 from limestone. In other words, the CO_2 generated comes from the limestone, i.e., not from a combustion reaction. Having said this, substantial portions of industrial sector emissions do result from onsite generation of process heat. Currently, the vast majority of this is generated from fossil fuels, which make up about 90% of the fuel mix. Bioenergy, while being by far the largest source of renewable industrial process heat, makes up only about 10% (IEA 2021).

According to the IEAs Net-Zero report, published in May 2021, industrial emissions will have to decrease by more than 90% globally between 2020 and 2050 for the world to have a 50% chance of limiting global warming to 1.5°C above pre-industrial levels. However, this is a global average meaning that in line with the equity and fairness (Common but Differentiated Responsibilities or CBDR) principles of the Paris agreement, industrial emissions in advanced economies effectively have to be zero in 2050 and decrease by 25% already by 2030 (IEA 2021). There can be no doubt that reaching this target will be highly challenging and require effective implementation of broad set of measures across the whole supply chain. These measures include things like improved energy efficiency and reductions in societal material intensity, but perhaps most importantly, a radical change in the way industrial process heat is generated, from a dominance of unmitigated fossil fuel combustion to technologies that generate close-to-zero greenhouse gas emissions.

It is important to note that underneath the umbrella term "industrial heat" lies a substantial amount of heterogeneity in that "heat" can come in many different forms and the demands of different industries and applications when it comes to heat quality can vary widely. As for the different possible zero-emission solutions, these can be classified under two main approaches: 1) adding carbon capture and storage (CCS) to existing fossil-fuelled processes or 2) switching to a clean form of energy used to generate the heat. Here as well though, there is a lot of heterogeneity across the different alternatives in terms of technological opportunities and challenges. In fact, this applies even just within the "biomass" category as well, as we will expand on further.

1.3 REPORT OUTLINE

Our objective in this report is to give an overview of the current status and future prospects for industrial process heat in terms of energy demands, heat qualities and the different low-emission options that are available. Specifically, we focus on the use of biomass-based energy carriers. In addition to technologically grounded analyses, we also discuss challenges to deployment of biomass-based industrial heat in the realms of policy and business models, and different strategies for how these challenges can be overcome. To this end, we draw upon a series of case studies carried out under the IEA Bioenergy auspices that analyse in more detail how solutions using biomass-based industrial process heat can be deployed in practice,

This report is structured as follows. In section 2, we give an overview of industrial heat demand across different applications and give a broad overview of different low-emission technologies that can be used to replace the fossil fuels that current dominate process heat generation. Section 3 discusses the economic and policy aspects around industrial heat and possible challenges facing companies aiming to transition to low- or zero-emission heat supply. In section 4, we draw upon the review in sections 2 and 3 to discuss a set of case studies carried out by IEA Bioenergy partners over the course of 2020 of five European companies that have implemented biomass-based industrial heat solutions. Finally, section 5 concludes with a broad discussion of the future developments when it comes to decarbonization of industrial heat and the role that biomass-based solutions can play.

2 Decarbonization of industrial heat - overview

As noted above, a key starting point when discussing industrial decarbonization is that many individual processes and applications across industries have been developed over a long time, in some cases for decades or even centuries (Bataille et al. 2018; Friedmann et al. 2019). Over time, the processes have been fine-tuned, made more efficient mainly with the objective to reduce costs and strengthen market competitiveness. However, further improvements are possible, and it is important to note that these include not just measures at the point of production itself, but also measures at the fuel sourcing and deployment stages, as well as at the utilization stage of the final products in terms of material intensity and efficiency. Table 2 lists a selection of measures to be implemented in order to decrease greenhouse gas (GHG) emissions across the full life cycle. While this list does not claim completeness, the overall point is that deep decarbonisation of this sector will likely only be achievable by strategically combining all available abatement opportunities.

Table 1: Overview of emission abatement options for different carbon streams in high-temperature industrial processes.

Options to reduce emissions from fuel use	**Options to reduce process emissions**	**Options to reduce product emissions**
• Fuel efficiency increase • Switching to biomass heat • Switching to solar thermal • Nuclear heat • Geothermal heat • Direct REN electrification (e.g. heat pumps, induction) • Indirect REN electrification (e.g. hydrogen, hydrogen derivates) • Biogenic or fossil carbon capture and storage • Providing flexibility to the electricity grid	• Process efficiency increase • Carbon switching (e.g. biogenic carbon) • Carbon capture and storage • Inter-industry material synergies • Inter-industry energy synergies	• Decreased material intensity • Material efficiency (e.g. lifetime expansion) • Reduce • Reuse • Recycling / Upcycling • Carbon utilization - secondary raw materials • Energy recovery • Substitution with other, lower-emission materials

However, while continued efficiency improvements and upgrading to best available technologies (BATs) are highly important emissions abatement tools, the best performing facilities are in many sectors approaching the limits of what is practically achievable in terms of process efficiencies (Bataille et al. 2018). This means that in order to reach the kinds of deep decarbonization targets that are required to comply with ambitions of global net-zero emissions by mid-century, technology shifts are needed. In the following, we give a literature-based overview of the characteristics both of the different kinds of industrial heat and the most important approaches to address greenhouse gas emissions arising from the generation of industrial process heat.

2.1 HEAT DEMANDS ACROSS DIFFERENT INDUSTRIES

Temperature is arguably the most important parameter when discussing different forms of industrial heat. Temperature demands on industrial heat can vary widely, from processes in e.g., steel and cement production that may require temperature far beyond 1000°C to some food industry processes that may need only 40-80°C for processes like homogenisation or pasteurisation (Naegler et al. 2015).

Before we go into more detailed mapping the heat demand across sectors and different options for decarbonization, it is worth highlighting that analysing and drawing general conclusions about industrial heat is methodologically challenging. This is not just because of the above-mentioned heterogeneity but also because industrial heat is typically generated on-site and not sold on open markets, which means that data availability is in general rather poor (Malico et al. 2019). Furthermore, most studies tend to divide industrial heat demand into categories based on temperatures, such as “low-temperature heat”, “high-temperature heat" and so on. However, there is no established consensus on where the boundaries between these are, so each study typically has its own categorization, as can be seen in Table 2.

STUDY REFERENCE	TEMPERATURE CATEGORIZATION					
Naegler et al (2015)	<100 °C	100-500°C	500-1000°C	>1000°C		
Philibert (2017)	<150°C	150-400°C	>400°C			
Bataille et al (2018)	<250°C	250-1000°C	>1000°C			
McKinsey & Co (2018)	<100 °C	100-500°C	500-1600°C	>1600 °C		
Malico et al (2019)	<100 °C	100-200°C	200-500°C	>500°C		
ARENA (2019)	< 150°C	150-250°C	250-800°C	>800°C		
Madeddu et al (2020)	<100 °C	100-400°C	400°C-1000°C	>1000°C		
Lenz et al (2020)	<100 °C	100-200°C	200-500°C	500-1000°C	1000-1500°C	>1500°C
IEA (2021)	<400°C	>400°C				

Table 2. Categorization of industrial heat across temperatures in some recent studies of the topic.

This lack of coherence in terms of categorization makes it challenging to give a good and simple overview of how different low-emission technology options match with temperature requirements. Having said this, overviews of the patterns across different industrial sectors in Germany and Australia, respectively, can be seen in Figures 1 and 2 below.

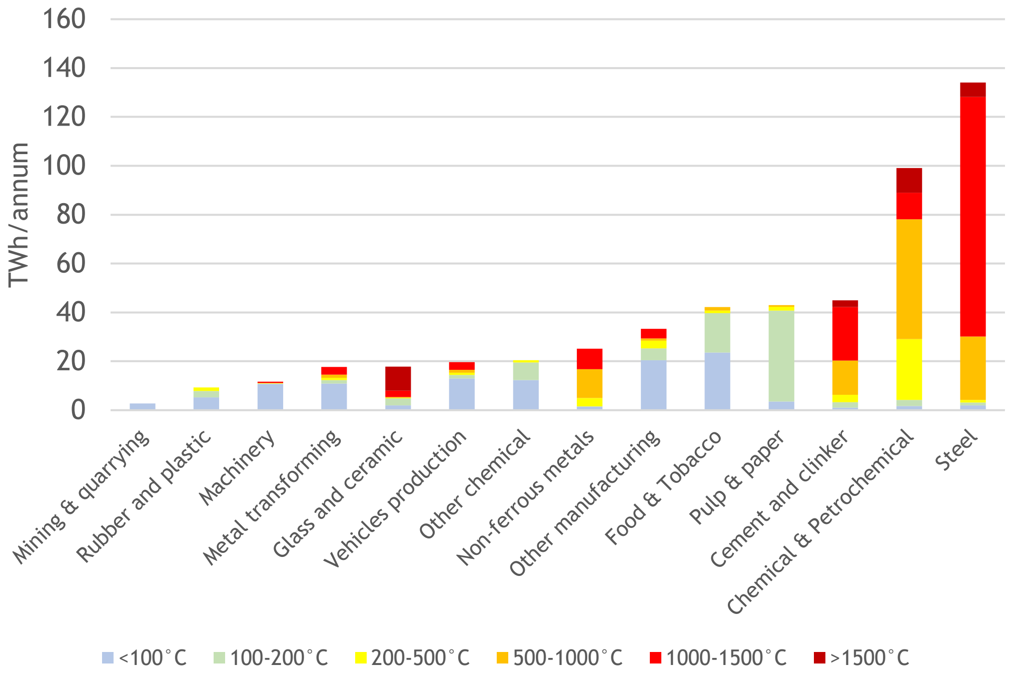

Figure 1. Industrial heat use in Germany in 2013. Data from Lenz et al(2020)

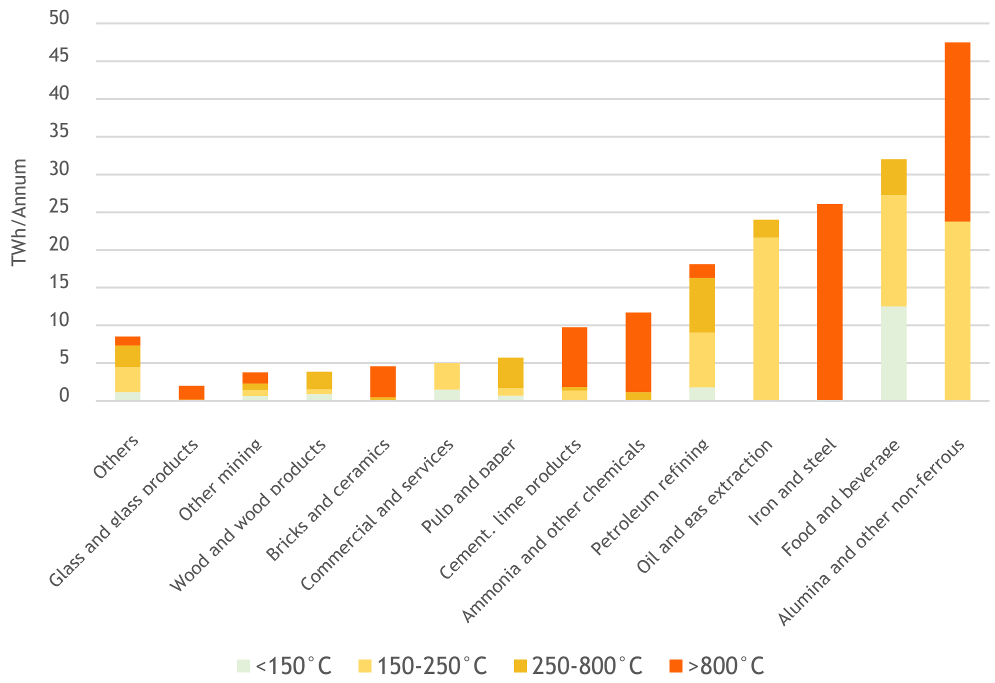

Figure 2. Industrial heat use in Australia in 2016. Data from ARENA(2019).

In addition to temperature, there are a few several other properties that are important to properly describe the characteristics of a particular process. These include control and flexibility - i.e., how and how rapidly temperature changes – and mode of heat transfer. For example, one clear pattern is that the very highest temperature demands – from roughly around 800˚C and above – are predominantly found in a few select sectors where these temperature levels are used to process minerals and metals. In these cases, the heat source tends to be in *direct* contact with the material to be processed, with key examples being blast furnaces or cement kilns, where in both cases the fuel or the flue gases chemically interact with the iron ore and the limestone, respectively. This can be put in contrast to the many *indirect* processes at temperatures around 200-500˚C that typically use steam as the medium of heat transfer, or where the material to be heated is enclosed in a vessel which is itself heated (Lenz et al. 2020; Malico et al. 2019). The direct/indirect aspect is important because the characteristics of **how** the heat is generated becomes much more important in the direct case. For example, flue gas composition or flame behaviour may be highly important for process performance and/or product quality (Thiel and Stark 2021).

2.2 OPTIONS FOR DECARBONIZATION OF INDUSTRIAL HEAT – AN OVERVIEW

As is indicated by Figure 4, most industrial process heat is currently provided by fossil energy. This is a pattern that is further strengthened for higher temperatures above 500°C, where fossil fuels dominate completely, with the main exception being the electricity used to produce (predominantly scrap-based) steel in electric arc furnaces.

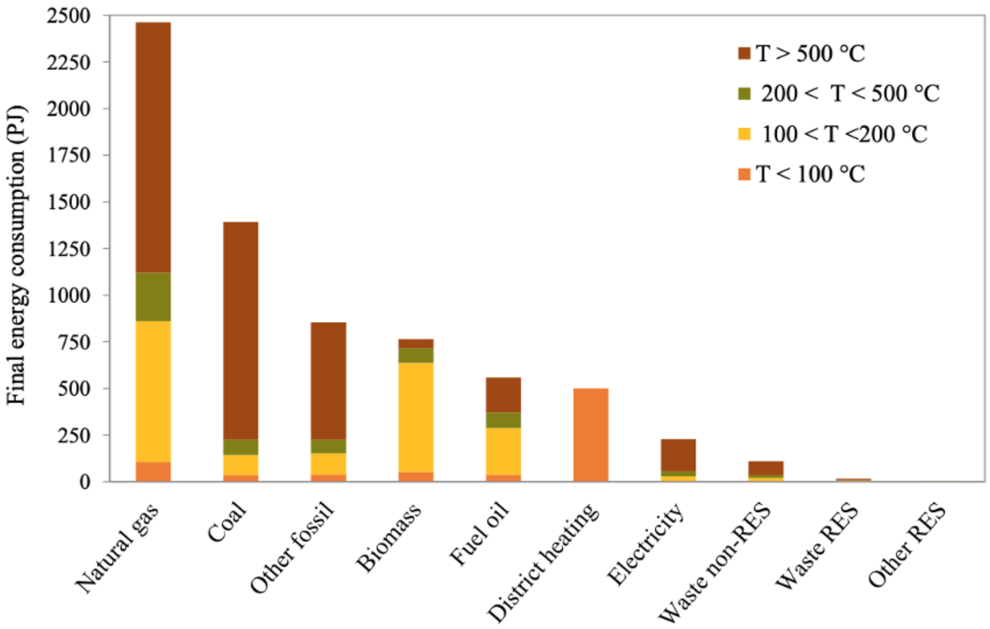

Figure 3. Energy carriers used for industrial heat in the EU-28, categorized by temperature levels. Figure from Malico et al. (2019).

Recent years have seen a fairly broad literature emerging on the different options - available as well in development – that could enable shifts to fossil-free industrial process heat. Our focus herein is on the role that biomass could play, but in order for this discussion to be set in the proper context, we first review the bigger picture of available alternatives. Acknowledging also the potential role of other emerging solutions, such as using solar thermal as part of portfolio solutions for industrial heat (e.g., Schoeneberger et al. 2020), we here focus on three groups of technologies: CCS (carbon capture and sequestration), electrification and hydrogen, before we shift our focus specifically to biomass.

2.2.1 CCS (Carbon Capture and Sequestration)

One of the seemingly most straightforward ways of enabling deep emission cuts is to maintain existing industrial processes and fuels but capture the CO_2 emissions and sequester these in geological formations. CO_2 capture and injection in geological formations are not new phenomena as such, as they have been implemented commercially for decades in e.g., the oil & gas sector, but the particularities of deployment vary quite substantially from sector to sector. This pertains both to the technological aspects of CO_2 capture, transport and storage, and to the market & policy context in question.

For the actual CO_2 capture, a few factors are especially important when it comes to determining the feasibility and techno-economic viability. A key issue is the composition of the CO_2-containing gas stream, where the CO_2 concentration is the central parameter – a higher CO_2 concentration typically means less energy is needed to separate out the CO_2 which can translate into lower costs of capture. A second key issue is whether the CO_2 emissions at the site are concentrated in one large point source or distributed across many smaller point sources? In this case the former is preferable and makes for lower costs, especially when it comes to achieving a high percentage of CO_2 capture. Thirdly, a key factor is whether there is onsite excess energy that can be used in the capture process. Here, it should be noted that different CO_2 capture processes have different requirements in both in terms of the volumes needed and whether the energy demand comes in the form of electricity or heat (Olsson et al. 2020).

Depending on the geographical context, the transport and storage stages of the CCS supply chain can be set up in different ways, with pipelines and ship transport being the key options for long-distance CO_2 transport. Pipelines tend to be more cost-efficient up to distances of 700-1200 km, but ship transport allows for more flexibility in that it enables many different capture sites to make use of one large storage site (Kjärstad et al. 2016), but also that ship transport makes possible more of an actual *market* for CO_2 storage services as it might entail less of a lock-in compared to if the capture site is physically connected to the storage site via pipeline.

A drawback of CCS is that it adds substantial costs but does not always add corresponding revenue - that is, unless a specific system is in place that places value on the function of the capturing and sequestration of CO_2. In other words, the commercial viability of an industry fitted with CCS rests upon the existence of an explicit or implicit price on CO_2, without which a facility with CCS makes no economic sense compared to a facility without CCS. An alternative approach that is increasingly discussed is carbon capture and utilization (CCU), which means that the captured CO_2 is made use of for productive purposes. The advantage of this is that this would allow for other ways of generating revenue than through a carbon price. The drawback though is that in many CCU applications currently under discussion – including the production of fuels or chemicals from captured CO_2 – carbon is locked in the product for only a relatively short time before being released into the atmosphere.

2.2.2 Electrification of industrial process heat

Up until around a decade ago, a common narrative in discussions on future global energy systems was that clean electricity would be expensive for the foreseeable future. Consequently, not only would deep decarbonization be impossible without a high price on carbon – electricity would also have to be treated as a precious resource only to be used where other options were not available. However, the subsequent reductions in costs of solar and wind power have led to somewhat of a paradigm shift in narratives around the role of clean electricity in the global energy system. The last couple of years have seen the rise of a stream of thinking that can be summarized as “electrify everything” (Olsson and Bailis 2019; Roberts 2017).

There are several different ways electricity can be used to produce process heat, including resistive heating, heat pumps, microwave heating and plasma technologies[1]. Regardless, in addition to the possibility to benefit from decreasing costs of wind & solar power, the use of electricity as a means to produce industrial process heat comes with other potential advantages that are related to rather fundamental technological characteristics. Compared to combustion-based heating, electricity-based heating tends to be easier to control, no local air pollution and have lower maintenance costs (Bartlett and Krupnick 2020; Rehfeldt et al. 2020).

In terms of commercial availability, electricity-based process heating is currently deployed across most of temperatures and scales, with electric arc furnaces used in metals processing (e.g., steel) working at temperatures approaching 2000°C and around 100 MW or more. However, there are in other sectors still technological aspects that limit the application of electricity-based process heating. These challenges relate especially to larger scales and very high temperatures (Rightor et al. 2020). Wiese & Baldini (2018) find that whereas it is possible to implement electric process heat in most applications below 250°C, this only applies

[1] Hydrogen could be seen as a form of indirect electrification if the hydrogen is produced from electrolysis, but we will nevertheless address hydrogen separately in section 2.2.3.

to about 25% of demand above 250° (see also Rehfeldt et al. 2020). There are solutions for higher temperatures that could eventually become broadly applicable, e.g., plasma generation, but these are thus far limited to scales of around 5-10 MW (Burman and Engvall 2019).

When it comes to lower temperatures, one particularly valuable technology is heat pumps. These can leverage one unit of electricity into multiple units of usable heat, as measured by the so-called coefficient of performance (COP)[2] which allows more efficient use of electricity. There are industrial heat pumps available that can provide industrial process heat at temperatures up to around 90°C with some manufacturers also offering solutions that can reach temperatures around 150°C, with 200°C potentially being within reach. However, it is important to note that the performance of a heat pump is highly reliant on the heat source and the heat sink, where efficiencies decrease with larger differences between the heat source and the heat sink. This means that heat pumps are particularly useful as a means to produce process heat by raising temperature of on-site waste heat streams (Marina et al. 2021).

In terms of challenges to electrification of process heat more broadly, operational cost remains one, as the cost reductions in wind & solar power generation are not directly reflected in actual grid power prices paid by industries. In many locations, industrial electricity rates are on a per-kWh basis substantially higher than corresponding prices of natural gas, meaning that - unless a heat pump solution is possible – policy support will be needed to cover the difference in operational expenses. This then is in addition to the capital expenses needed for transition – electricity-based heating systems tend to require substantial conversion investments. For this reason, they might be more promising in greenfield rather than in brownfield settings (Bartlett and Krupnick 2020; McKinsey & Co 2018).

2.2.3 Industrial process heat from hydrogen

Hydrogen can be produced via several different pathways, including gasification of hydrocarbons or biomass, steam methane reforming (SMR) of natural gas, or electrolysis, where the latter entails the use of electricity to split water into hydrogen and oxygen. The vast majority of global hydrogen volumes used today are produced from fossil fuels, primarily through SMR. However, recent years' substantial increase in the interest of how hydrogen can enable global emission reductions are largely based on anticipations of lower future costs of so-called "green hydrogen", i.e., hydrogen produced via electrolysis powered by renewable electricity (Material Economics 2020). In addition to providing process heat, hydrogen can play several other roles in the field of industrial decarbonization as well. This includes as a chemical component in synthetic hydrocarbon fuels and materials (e.g., Palm et al. 2016; Ueckerdt et al. 2021) and as a reducing agent in primary[3] steel production (Vogl et al. 2018).

When it comes to the use of hydrogen as a means of providing process heat, it can offer opportunities for relatively smooth integration into, or replacement of, process heat systems based on fossil gases such as natural gas or LPG (liquid petroleum gas). Hydrogen is also a gas and can provide very high temperatures. However, retrofitting existing gas-based heating systems to work with hydrogen does come with several caveats. Not only is hydrogen transport and storage more difficult and expensive, its combustion properties also differ somewhat from natural gas in e.g., that it burns more rapidly with a flame that is nearly invisible (Friedmann et al. 2019). Furthermore, heat transfer materials might also have to be retrofitted (Bartlett and Krupnick 2020).

Cost-wise, production of process heat using hydrogen is still quite challenging, especially in locations with readily available natural gas. For example, according to IRENA (2020), costs of green hydrogen are currently between 3-6 USD/kg (largely depending on electricity costs). Even if costs are reduced to around 1 USD/kg,

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[2] A COP of 3 means that for every unit of electricity fed into the heat pump, 3 units of usable heat is produced.

[3] Primary steel is iron ore-based as opposed to secondary steel which is based on recycled steel scrap.

a 60 USD/tonne CO_2 price would be required in the US for it to be competitive as a source of process heat in cement production, although this to a large extent is a consequence of the low costs of natural gas in North America (Bartlett and Krupnick 2020).

2.2.4 Biomass-based process heat in industrial sectors

As is the case for electricity-based process heat, biomass-based process heat can come in many forms. Not only is there great heterogeneity when it comes to the different forms of biomass feedstock, depending on the pre-processing, the biomass can be turned into several different fuels, that can be solid, liquid or gaseous. These can vary substantially in energy density, combustion properties and logistic characteristics. For example, wood chips can either be burned directly or after having gone through torrefaction. Alternatively, the wood chips could perhaps have been gasified to produce hydrogen, processed further into bio-methane or used to produce pyrolysis oil (Friedmann et al. 2019; Rehfeldt et al. 2020).

This means that biomass-based options can in principle fulfil the process heat needs of most industrial use cases (Malico et al. 2019), but the specific nature of the process and the industry in question will determine what kind of biomass-based process is applicable. For example, glass and ceramic sectors require temperatures above 500˚C and a gaseous fuel to have clean combustion, which means that for this particular case, raw wood chips would not be feasible, but bio-methane produced from the same wood chips is a promising option at least from a technological perspective (Lenz et al. 2020). In addition to the wide range of process applications wherein biomass can be useful, an additional advantage compared to other forms of renewable process heat include the possibility to store fuels for long periods of time, although it should be mentioned that storage can be quite demanding in terms of space depending on the fuel. Another advantage of biomass is that when combined with CCS to bio-CCS or BECCS, it enables the generation of carbon dioxide removal (CDR) from the atmosphere, also referred to as negative emissions (Olsson et al. 2020).

Despite its potentially broad usability across different sectors and temperatures though, biomass is currently predominantly used for provision of process heat at temperatures around or below 200˚C (see Figure 4). The largest volumes are concentrated in a few select sectors, especially forest industries in the form of sawmills and pulp & paper mills. As can be seen in Figure 5, almost 90% of the biomass used for industrial process heat in the EU-28 in 2017 was consumed in forest industries.

The reason why the use of biomass for process heat is so prevalent in forest industry sectors is that large amounts of biomass become available on-site as part of the key industrial processes themselves. Bark and sawdust are produced in large amounts as residues at sawmills and can be burned to produce heat used for drying of lumber. Similarly, at pulp & paper mills, residues in the form of bark and waste liquors (in Kraft mills) are burned to produce process steam as well as to generate electricity (ARENA 2019; Malico et al. 2019; Philibert 2017). By using biomass process residues, the use of fossil fuels can often be avoided. If the available residues in these sectors would not be used, an additional waste disposal problem would arise.

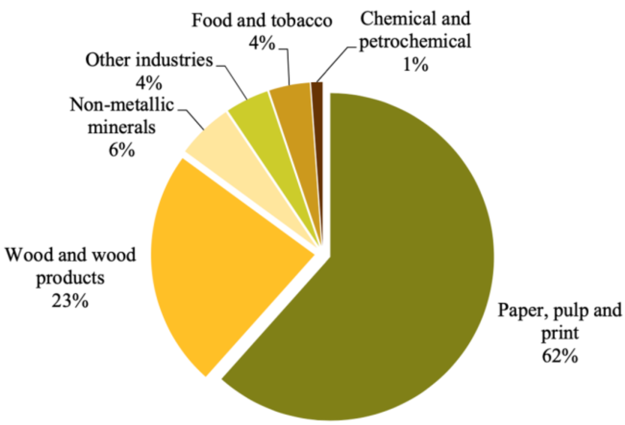

Figure 4. Use of biomass for industrial process heat across different sectors in the EU-28 in 2017. Figure from Malico et al (2019).

The “non-metallic minerals” sector referred to in Figure 5 is predominantly made up by the cement sector, which for decades has used different forms of solid waste materials, a portion of which are of biogenic origin, to replace fossil fuels in the form of e.g., coal and petroleum coke (Lenz et al. 2020).

The use of biomass in cement production is a practical example of an exception to the otherwise dominating pattern that biomass is used for relatively low temperatures and in forest industry sectors. Some argue that there is somewhat of a lost opportunity here, in that instead of being used to produce heat at temperatures where electricity-based options such as heat pumps could work, biomass should be used for purposes where other options are scarce (Lenz et al. 2020; Material Economics 2021). Leaving aside if/how this ambition should be supported, a key question that remains is whether and how biomass process heat can be made use of in other sectors. One challenge is that it is difficult to make general statements as biomass prices can vary widely between different locations. Material Economics (2021) note that in places where biomass can be made available at costs of 2-4 €/GJ, it can be quite competitive. However, actual costs for larger volumes can often be more in the order of 6-8 €/GJ, which makes for a quite substantial barrier to competitiveness. In addition, Malico et al (2019) identify high investment costs, feedstock availability and security of supply as key obstacles to uptake of biomass-based process heat in non-forest industry sectors.

3 Policy options for decarbonization of industrial process heat

3.1 BROAD POLICY PORTFOLIO NEEDED…

Regardless of whether switching to biomass process heat for high-temperature continuous industrial application is considered or alternatives process routes - or process route combinations - are envisaged, certain barriers have to be considered, especially in sectors like steel & petrochemicals which largely produce commodity-type products. By definition “commodities are intermediate goods available in standard qualities” which have “competitive, liquid and international” markets (Olsson et al. 2016). Thus, profit margins can be expected to be low and “capital costs are focused and upfront”. This results in a general inability to “pass on [costs] without losing market shares” while innovation benefits cannot be captured within a satisfying time horizon (Bataille 2019). Consequentially, implementation of measures that result in cost increases will seldom be implemented in the absence of policy measures that, one way or another, create conditions that either reduce the costs or allow for means by which the added costs could be met by corresponding revenues.

A selection of policy options for emission abatement in heavy industry is collected in Table 3. What can be said is that similar to how all abatement opportunities (circular material flows, improved process efficiency, fuel switching etc.) will be needed, a broad portfolio of policies throughout all life-cycle steps will be necessary.

Table 3: Policy measures and options for emission abatement in heavy industry. Source: own compilation based on (Bataille 2019; Coninck 2019; Koca et al. 2020; Rissman et al. 2020; Uppenberg 2019)

Innovation & investments	• Sustainable taxonomy, green investment and divestment • R&D financing based on degree of bankability (e.g. Innovation Fund, Horizon Europe, IPCEI, EIB, EFSI) (Uppenberg 2019) • Investment risk reduction, tech warranties, templates for simple and accurate contractual schemes for renewable heat and power delivery • First-of-a kind subsidies and infrastructure support
Fuel and process attributes	• Best available technology (BAT) reference documents • Phase-out and sunset clauses for high emissions technology • Eco-design measures including emission back-pack of raw-materials • Carbon pricing, cap and trade, CO_2 taxing
Product attributes	• Fight against premature built-in obsolescence • “Right to repair” for material intense end-user products • Harmonized rules for labelling embedded product emissions, product environmental footprints (PEF), electronic product passports
Circularity attributes	• Restriction on landfilling • Separate waste collection models • Mandatory recycling contents • Market observatory for key secondary materials • Extended producer responsibility (EPR) schemes • Waste trade limitations • Strategies for reduce, remove, re-use and re-cycle
Market-based	• Create markets for low GHG materials via public and private procurement • Carbon borders and border tax adjustment • Extending registration, evaluation, authorization and restriction of materials (“no data no market” principle based on REACH)
Information exchange & monitoring	• Education and consumer awareness for and of low-carbon materials • Promoting digital technologies for tracking, tracing and mapping of resource • Monitoring, stakeholder and financing platforms • Improvement of statistical data collection and joint and open-access dataspaces • Transparent mapping of carbon lock-in lobbying (Coninck 2019)

3.2 …BUT SOME INSTRUMENTS WILL BE PARTICULARLY IMPORTANT

While there is a need for a broad and multi-faceted set of policy measures to meet the steep challenge of achieving net-zero emissions by 2050, the short timeframe and the radical changes needed will require focus on a few select policy measures that are particularly important to meet challenges that are specific to the industrial sector.

3.2.1 Scale up-funding to bridge the demonstration project valley of death

Regarding innovation, investment and financing, there is a need for policy support mainly to overcome the barriers related to high upfront investments in immature technologies. One particularly important challenge here is to fund scale-up and especially close-to-commercial demonstration facilities where the capital needs quickly can become very large but where the risk involved is often too large for companies to be able to take on themselves. An example of a promising policy instrument here is the EU's so-called Innovation Fund which has been set up to fill this gap in funding for industrial decarbonization efforts. Through the Innovation Fund, companies can get support not just for capital expenditures needed for demonstration projects, but for operational costs as well (European Commission 2019).

3.2.2 Making carbon pricing work for companies working in global markets

As was noted above, a key challenge when it comes to designing climate policy aimed at industrial emitters compared to e.g., the power sector, is that many industries compete in international and sometimes global markets whereas the latter are usually substantially more limited in geographical scope. Consequently, introduction of carbon pricing in a specific jurisdiction can lead to reduced competitiveness of industries within the jurisdiction relative to competing industries outside the jurisdiction. There is a risk that this results in production relocating to locations not affected by the carbon pricing, meaning that the whole purpose of the policy measure – i.e., emission reductions – would have been lost. This phenomenon is typically referred to as "carbon leakage" and has been very much debated in relation to the EU Emission Trading System (ETS),

The EU ETS includes both the energy sector and the industrial sector. However, industries deemed to be at risk of carbon leakage do not have to buy all the CO_2 emission allowances needed to cover their emissions. Instead, they receive a certain portion of the needed allowances for free. However, the EU is currently in the process of instead dealing with the carbon leakage problem by introducing something called a carbon border adjustment mechanism – CBAM – also sometimes referred to as "climate tariffs" or "carbon tariffs". The idea behind these is that non-EU companies exporting into the EU would pay a tariff corresponding to the cost of the ETS allowances that the company would have to buy if it was operating within the EU. Exactly how this is to be implemented is still under consideration. Key questions that remain concern how the CO_2 footprint of non-EU goods is to be determined, but also how the current mechanism of free allowances is to be phased out as the CBAM is phased in (European Commission 2021).

3.2.3 Creating demand for more expensive low GHG heat

The measures needed to enable deep cuts in the emissions from industrial process heat will in many cases will entail increased costs from higher capital expenses (capex) and/or higher operational expenses (opex). Some of these costs may decrease over time as key technologies mature, but in at least an introductory phase there is a need to for policy to create markets. Demand creation policies can come in rather many different forms with different approaches being more appropriate in some sectors than in others. For example, public procurement guidelines could be an appropriate instrument to use for decarbonization of cement, because a large share of the cement & concrete used in society tends to be used in construction projects that fall under public procurement regulations (e.g., Pädam et al. 2021). The same cannot really be said for steel, whose uses are more broadly distributed across the economy. Here, an option could instead be to mandate that key steel using sectors – e.g., the automotive or white goods sectors - meet certain targets that relate to greenhouse gas emissions in their supply chain. Interestingly, while such regulations planned to be introduced in the EU, none are yet in place in the EU, European car and truck manufacturers have already begun to commit to decarbonization of their supply chain. This has accelerated in the last couple of years to the point where these commitments correspond to a demand for low-GHG steel amounting 20 million tonnes by 2030, substantially more than all the low-GHG steel production currently planned.

While the impending regulations on supply chain emissions constitute a reason for the increased demand for low-GHG steel from the automotive sector, other factors are in play as well, including an ambition among car companies to differentiate themselves in marketing as “green”. Carried forward to the sticker price of a car, the cost increase resulting from using low-emission steel can be on the order of <1%. It is expected that consumers will be willing to accept this in return for getting a car with a very low supply chain emissions footprint (ETC and Material Economics 2021).

3.2.4 The elusive green premium?

Whether consumers are willing to pay this “green premium” is an important question and one that varies not only between sectors and consumer segments but over time as well. It is typically assumed that industrial process heat is so detached from public awareness that consumer-focused approaches that are feasible for goods like food and LED lightbulbs are not applicable to e.g., industrial heat (Friedmann et al. 2019). Growing public awareness about the importance of climate change mitigation and investor pressures on companies may be about to change this but making these kinds of strategies work will require new approaches, so that any premia that consumers are willing to pay can be passed along the value chain accordingly. Companies in different stages of the value chain may also have to cooperate more closely than historically has been the case in e.g., globally traded commodities where things like traceability and supply chain transparency run counter current to how these markets have functioned historically (Freidberg 2017).

4 Practical experiences: analysis of 5 cases

4.1 Presentation of the five case studies

To connect our broad conceptual discussion in the preceding sections to experiences of practical implementation, we here draw on five case studies that have been carried out as part of the IEA Bioenergy inter-task project on the use of biomass for provision of high-temperature heat in industry.

The **first** case study (Koppejan 2020) describes how a potato processing company in the Netherlands installed a biomass-based process heating system to partly replace an earlier one based on natural gas. The process heat to be supplied is made up of steam with a temperature around 215°C and the biomass solution is used to act as a baseload heat source, with a gas-based solution used for peak load. The latter is still based on natural gas although there are tentative plans to instead use biogas produced from internally generated biomass residues. The biomass for the baseload boiler is made up of low-grade wood residues generated by pruning activities done by municipalities in the vicinity of the facility. In terms of non-technical factors that were important for successful implementation of this project, key aspects include the availability of low-cost fuel and a proactive engagement with local stakeholders in the planning and execution phases of the project.

The **second** case study (Grootjes et al. 2020), is based on a recycled paper-based pulp & paper company in the Netherlands which used gasification of site-generated paper rejects to replace a third of the natural gas used at the site, with a 30% reduction in costs annually spent on water, gas & electricity. Gasification as a technology was seen as favourable as it enabled smooth integration in the existing gas-based heating system. Furthermore, it is not very sensitive to feedstock quality variations, although the project did require introduction of processes aimed at control of fuel quality. A key aspect to be aware of related to the switch from natural gas to a gasifier-based solution is that the latter is more labour-intensive and required additional staff amounting to three full time equivalents. Also, despite the reduction in fossil fuel use that was the aim of the project, there was quite a bit of local opposition from NGOs, potentially owing to a general scepticism towards waste processing projects. However, the reduction in truck transports that would result from the implementation of the project eventually led to local support of the project.

The **third** case study (van de Beld and Toussaint 2020) describes the installation of a solution based on fast pyrolysis bio-oil (FPBO) at a dairy factory in the Netherlands. In this case, a solution based on solid biomass was not possible partly because of limited space locally available and partly because of a need to have a fuel that could be co-fired with natural gas so as to be able to use this as back-up. Opting for FPBO solved both these issues. It is more energy-dense, which means that it takes up less space on site and being a liquid, it is easier to store and can also be transported across the site in pipelines. Other advantages include a lower capex compared to a solid fuel system. The FPBO is produced off-site from wood pellet crumbles and delivered 30 km by truck to the dairy factory. Being an innovative technology solution, the project could receive public support amounting to 40% of the investment and also benefited from a contract-for-difference type system for renewable heat that was valid for the first 12 years of the plant's operation. In addition to these financial incentives, a long-term off-take agreement between the fuel supplier and the dairy plant was key to provide enough certainty for both parties to make the necessary investments and commitments.

The **fourth** case study (Bristav 2020) is focused on a paper mill in Sweden and its process of shifting from oil-based heating to instead using municipal solid waste. The manufacture of paper tends to be very energy intensive, requiring substantial amount of process steam at temperatures around 200°C. Before the shift to MSW, this was supplied using heating oil, which however proved problematic in the time period 2005-2008 that saw very high and drastically fluctuating oil prices. This led to a project aimed at finding another way of generating process heat. The choice to go for municipal solid waste was predominantly done on purely economic grounds, as the fuel itself comes with a "negative price" in the sense that waste management companies can charge so-called "gate fees" for receiving waste for treatment. This made the shift from heating oil to MSW financially viable despite the high capex of the waste-to-energy (WtE) facility that had to be constructed, as well as the fairly high non-fuel operational expenditures. In addition to providing process steam to the paper mill, the WtE plant also generates electricity and provides district heating to a nearby village. In addition to the viability of the business model itself, a key factor in enabling this project was that 20-year fuel supply contracts could be signed which provided an important degree of de-risking.

The **fifth** case study (Nussbaumer 2021) presents a project where a biomass-based process heating solution was implemented at Switzerland's largest bakery. An important component of the rationale for the project was to utilize grain residues generated further upstream in the supply chain at a mill operated by the same company that owns the bakery in question. The fuel mix used is composed of 50/50 grain residues and wood chips, though it is possible to run on 100% wood chips as well. In addition to the biomass boiler, the bakery also has a gas-fired peak boiler to allow for more rapid changes in heat load.

4.2 ANALYSIS OF THE FIVE CASES

A pattern that we touched upon in section 2.3 is that biomass tends to be used for process heat primarily in sectors where there for one reason or another are substantial amounts of biomass on-site in the form of residues or by-products. Four out of five cases reviewed above are exceptions to this pattern and show that it is quite possible also for other sectors to find ways of using biomass for process heat where both the technological and financial aspects pencil out favorably.

An observation that can be made about these five examples of how biomass can be used to replace fossil-fuel based heating in industry is that they showcase a key point that we discussed in section 2.3, namely that biomass-based process heat can come in many forms. Our five cases include solid waste biomass, gasified paper rejects, fast pyrolysis bio-oil (FPBO) based on wood pellet crumbles and finally municipal solid waste. What this goes to show is that from a technological point of view, biomass-based solutions can provide a very broad variety of tasks when it comes to supplying industrial process heat. This however also points to the importance of careful analysis not just of the specific process in question, but also the site and the local fuel availability situation.

In the first three examples, the fossil fuel being replaced is natural gas, and here we get a good overview of some different ways in which biomass-based process heat can be integrated in facilities originally designed to work with gaseous fuels. In case 2 (gasification of paper rejects) and case 3 (FPBO), this is made possible by pre-processing solid biomass to gaseous and liquid form, respectively, to obtain a fuel that would fit with plant-specific conditions. Cases 1 and 5 are cases of biomass replacing gas, but doing so using a somewhat different approach, where the overall system design is changed, using a combination of a system based on solid biomass as baseload and a gas-based solution for peak load. As was noted in section 2, a key advantage of gas-based (and electric) heating is the possibility to smoothly adjust heat output. However, it may not be necessary to have this flexibility across the full 0-100% span of heat output. It might very well be possible to have a baseload/peak load setup using two different heating systems, where one has a larger capex and lower opex and hence is well-suited for steady load across many operating hours (in this case the solid biomass boiler) and another which has a lower capex but higher opex and hence is suited for use during a smaller number of hours.

An important common theme across all the cases is the importance of strong long-term relationships between the industry using the fuel and key partners, especially in terms of fuel supply. This shows the importance of value chain coordination and cooperation in making implementation of biomass-based process heat solution successful, i.e., actors need to think in terms of broad systems and not just about replacing one piece of hardware with another.

Finally, it is worth noting that three out of five projects have been carried out with cost reductions as the primary objective and based on identification of a viable business case. The observation that there are examples where phasing out fossil fuels is economical even in the absence of strong policy measures in the realm of process heat is very welcome. However, in order to get a broader uptake of low-emission process heat solutions, there is a need for policy mechanisms that make sure that the economics work even if the cost - on a non-policy basis - will increase.

5 Discussion

This report has aimed at providing an overview of different options for decarbonization of industrial heat, with a particular focus on the role of biomass. Given the rapid technological development currently in place, it is difficult to make forward-looking analysis with an acceptable level of certainty. What we can do in conclusion though is present some general characteristics of biomass as a means by which to phase out fossil fuels from industrial heat provision.

From a purely technological standpoint, the potential of bioenergy as a source of industrial heat is quite promising in that it can be used across almost the full range of temperatures needed, be it sub-100°C uses in food industry or above 1000°C in metals and minerals processing. This is a consequence of how biomass can be turned into energy via many different pathways, ranging from direct combustion to gasification or liquefaction whereby it is possible to produce fuels that are very similar to incumbent fossil alternatives in terms of chemical composition and performance. However, this may require pre-processing that can be costly and based on technologies that are still in various stages of development and up-scaling.

This relates to a key question around costs and how the viability of biomass-based process heating hitherto has been contingent upon local availability of low-cost biomass resources that are not in demand in other sectors. If this continues to be the case, the increases in the use of biomass for industrial heat that is needed to meet the IEA's net-zero pathway are unlikely to be achieved. As it is unlikely that vast amounts of readily available and very low-cost biomass would become available on global markets any time soon, public policy needs to step in and create the conditions that make low-GHG process heat options economically viable even if they entail increased costs.

These kinds of policies will anyway be necessary for some technologies and some sectors. An enlightening example here is cement, which is one of the few sectors where close-to-zero emissions will by virtually all estimations be impossible without CCS. In contrast to e.g., how battery electric vehicles (BEV) are likely to soon become cost-competitive with internal combustion engines (ICE) once BEV supply chains have scaled and matured, there is no chance that scale-up and experience curve effects will result in cement *with* CCS costing less than cement *without* CCS. That is, unless a policy is set up specifically to enable this. Similarly, broader deployment of biomass-based process heating will also in many cases add cost compared to fossil fuels whose external costs remain largely unaccounted for. The point is here that innovation policies that are designed to phase in new technologies will not suffice – there will also be a need to provide long-term certainty of operating cost coverage and business model viability.

However, while the negative external effects of fossil fuels are unaccounted for, biomass-based solutions have many existing or potential positive external effects that if priced could add value corresponding to some of the added cost. These kinds of values can come in the form of enabling climate-smart forest management practices that would otherwise be economically challenging, such as preventing wildfires by removing fuel from woodlands. Another key opportunity is the use of biomass in combination with CCS to generate negative emissions. This is a potential feature that is unique to biomass-based industrial heat and one that holds much potential to be an important tool in the climate change mitigation toolbox if the right policy and market frameworks are set up. Furthermore, in the cement sector, even reaching zero-emissions might not be possible without bio-CCS(Yang et al. 2021).

Finally, we saw in the both the first and the fifth case study examples of how a solid biomass-based process heat solution was used as baseload and with a gas-based heating providing flexibility and peak load. While the peak load solutions need to be decarbonized as well for this approach to be compatible with zero emission ambitions, this portfolio-type approach to industrial heat looks quite promising. It can also be seen as an analogue to the general societal challenge of decarbonizing industrial heat, where many different solutions will likely be needed and combined to enable net-zero compatible industrial heat production and global decarbonization of the industrial sector.

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