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1.2.1.

Climate-induced impacts on energy demand and supply

Energy mix and emission factors: a local approach

The decarbonization of "hard-to-abate" sectors

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Executive summary

This policy brief includes three different research contributions to energy economics and decarbonization challenges.

One research investigates the relationship between climate change and global energy dynamics, considering both demand and supply aspects. In terms of energy demand, the study introduces a novel methodology to disentangle the impact of weather shocks and long-term climate variations on electricity and fossil fuel demand in 134 countries from 1970 to 2019. On the energy supply side, the study explores the potential consequences of extreme weather events on power markets, emphasizing potential volatility in electricity prices and increased costs for managing the grid during high-demand periods. The findings show that consumers respond to average weather conditions over many years, influencing new technology adoption and adjustments in energy-efficient appliances. It also addresses the implications for power generation, emphasizing the need for flexible technologies during extreme weather conditions.

A second research considers the pivotal role of Marginal Emission Factors (MEFs) in evaluating the relationship between energy generation and the reduction of greenhouse gas emissions. While the Average Emission Factor (AEF) is a common metric, the study argues for the more accurate assessment provided by MEFs, representing the amount of greenhouse gases emitted per unit of economic or energy activity. The need to consider MEFs at a regional level is emphasized, particularly in segmented electricity markets such as Italy's, comprising zones that differ in their power supply arrangement. The research explores the methodologies for assessing MEFs, distinguishing between inter-day and intra-day approaches. MEFs are crucial for policymaking: they inform emissions standards, guide efforts to decarbonize the electricity grid and prioritize investments in grid infrastructure. In essence, estimating MEFs is shown to be a critical step in crafting effective energy and environmental policies.

A third study explores new technologies supporting the gradual decarbonization of challenging industrial sectors. Focusing on fuel and industry, the study also evaluates the implications for the financial sector, considering both risks and opportunities. The analysis distinguishes between three main approaches for decarbonizing heavy industries: material modification, process innovation, and emission management. The study emphasizes the urgency of addressing hard-to-decarbonize heavy industries and highlights the importance of building European industrial strategies and resilient raw material supply chains to align with decarbonization paths.

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1. Presentation and description of the research activity undertaken

1.1 Climate-induced impacts on energy demand and supply

1.1.1 Energy demand

In this research we infer long-run climate impacts on energy demand with a novel methodological contribution: separating the effect of weather shocks from that of climatic variations over time in each location.
The novel empirical method is able to i) identify the causal impact of short- and long-term adaptation; ii) project real future long-term impacts on energy demand, along with additional fluctuations from weather shocks. We estimate the response of electricity and fossil fuel demand to Cooling Degree Days (CDDs) and Heating Degree Days (HDDs) for five production sectors exploiting a panel dataset of 134 countries over the period 1970- 2019.

1.1.2 Energy supply

Unforeseen pressure on power marker operation during extreme weather events can lead to higher volatility in electricity prices, higher grid management costs and power outages at times of high demand.
Thermal electricity generation and renewable technologies may be at physical risk due to heatwaves and extreme weather events. The study aims to assess the potential unavailability of thermal and hydropower generation units due to extreme temperatures by using a regression model on power outage data collected in Europe between 2018 and 2022.

1.2 Energy mix and emission factors: a local approach

Climate change mitigation policies require an assessment of the connection between renewable energy generation and the reduction of greenhouse gases. Specifically, in the electricity sector, this entails examining how the production of electricity from Renewable Energy Sources (RES) impacts CO_2 emissions (Bretschger and Pittel, 2020).

The most straightforward approach to tackle this matter is by calculating the ratio between emissions produced by a particular power system and the corresponding power generation during a specific timeframe. This metric is known as the Average Emission Factor (AEF). However, the AEF disregards the composition of the power generation mix in the system and overlooks the dynamic shifts in the merit order of power supply.

An accurate measure of the sensitivity of carbon emissions to changes in load would be represented by the average emissions of marginal plants, commonly referred to as the Marginal Emission Factor (MEF). MEFs refer to the amount of greenhouse gases (GHGs) emitted per unit of economic or energy activity. Their estimation is crucial for GHG emissions reduction.

In the initial phase of the research project, we gathered essential data to estimate the MEF related to electricity generation and carbon emissions. We will contribute to the literature by expanding our analysis to possible evolutions of electricity markets.

1.3 The decarbonization of "hard-to-abate" sectors

This research aims to investigate new technologies to support the gradual decarbonization of industrial sectors, in particular those known as "hard-to-abate". In the short term, it is necessary to implement an effective process for reducing CO_2 emissions across the full lifecycle of a product or service. Unfortunately, no silver bullet exists when it comes to decarbonizing the "harder-to-abate" sectors.

The research focuses on two main areas where decarbonization is urgent: fuel and industry. In addition, the implications for the financial sector, both in terms of risks and of opportunities, are evaluated. In this study, the research group was supported by Frost & Sullivan, a US company founded more than 60 years ago with over 1,000 experts, who have proven strategies and best implementation practices to help their clients to meet challenges and to identify new opportunities for transformational growth.

2. Relationship with the existing literature on the topic

2.1 Climate-induced impacts on energy demand and supply

2.1.1 Energy Demand

Empirical work aimed at the identification of climate effects from weather variations is based on strong assumptions about dynamic processes such as adaptation and the persistence of idiosyncratic temperature responses amid secular climate change (see Dell et al., 2014; Deryugina and Hsiang, 2017; Newell et al., 2021; Burke et al., 2015, Kalkuhl and Wenz, 2020, Rode et al., 2021, Wenz et al., 2017 and Auffhammer et al., 2017). The innovations we propose here relax the assumption that we cannot exploit meaningful climate variation in a panel of aggregated annual country observations. Inspired by the model and results of Bento et al. (2023), we propose an advance in the identification of future climate change impacts. The key hypothesis behind our empirical framework is that we can observe a sufficiently large climate variation in units over decades. Based on such an assumption, we break the meteorological variable down into two components: slowly varying climate and idiosyncratic annual variations from the expected climate.

2.1.2 Energy Supply

Climate change can impact energy systems not only by increasing demand but also by affecting the efficiency of thermal electricity generation and renewable technologies (Bosello et al., 2012). Additionally, it can reduce transmission and distribution capacity, further challenging the operation of electricity grids (Roson and Van der Mensbrugghe, 2012). Most of the literature has so far focused on how reduced water availability due to climate change can undermine the electricity generation of hydroelectric dams (Van Vliet et al., 2016; Solaun and Cerda, 2019). Yet, coal and nuclear power plants can be severely affected during droughts due to variations in streamflow levels and temperatures, affecting the availability of the cooling water needed to generate at full capacity (Bartos et al., 2016). Gas-fired power plants can be affected by a reduction in the efficiency of turbines due to extreme ambient temperatures (Coffel and Mankin, 2021). Extreme weather events can also affect renewable generation (Jarez et al., 2015). Only a limited body of empirical studies has estimated how climate change will affect thermoelectric power plants (Behrens et al., 2017).

We study the potential unavailability of thermal and hydropower generation units due to extreme temperatures by developing a regression model based on outage information collected from 2018 to 2022 in Europe. The dataset includes information on over 21,000 outages. The method adopted partially follows previous analysis (Dell et al., 2014), but expands on the literature by providing country-specific and fuel-specific responses.

2.2 Energy mix and emission factors: a local approach

In a seminal paper by Hawkes (2010), the MEF for the GB electricity system was calculated. Since then, the growing body of research on MEF has considered various facets of the analysis. Numerous studies have estimated MEFs in multiple countries, examining the relationship between MEF and the Average Emission Factor (AEF). Notable examples include Siler-Evans et al. (2012) and Ryan et al. (2016) for various U.S. systems, Bettle et al. (2006) and Jansen et al. (2018) for the British system, Voorspools and D'haeseleer (2000) for Belgium, Oliveira et al. (2019) for the UK, France, and Spain, Kofi et al. (2017), Climate Transparency (2017). Beltrami et al. (2020) computed the MEFs for Italy, excluding RES generation, at the national scale. Nevertheless, the Italian electricity market is segmented into six distinct zones, each characterized by its unique power supply arrangement. The national MEF is an aggregate figure, representing a weighted average of MEFs for these individual zones. From a policy perspective, it becomes imperative to scrutinize the MEFs for each of these zones.

Some scholars have explored the role and significance of RES in accurately calculating MEF (see Hawkes, 2010, 2014 and Li et al., 2017). Beltrami et al. (2022) have shown that RES could act as marginal sources in the Italian power exchange market and that market operators have often placed non-zero price bids for electricity generated by RES. This raises questions about the validity of excluding RES from MEF calculations in a system with a significant penetration of renewables, such as the Italian electricity market.

Another strand of academic research has been dedicated to developing the appropriate empirical methods for assessing the Marginal Emission Factor (MEF). In particular, the day-ahead electricity market is structured as 24 hourly sub-auctions, where power plants are dispatched based on the merit order, and equilibrium quantities and prices are determined for each hour of the day. Hawkes (2010) adopts what is known as the inter-day approach. However, this approach treats consecutive hours as unrelated, overlooking the fact that various dynamic constraints in power system operations lead to non-convexities in production costs. Hence, an intra-day approach has been developed (Beltrami et al., 2020), which enables the measurement of MEF for shorter time intervals.

Nevertheless, the intra-day approach necessitates complex data analysis because power data exhibit daily and weekly patterns that must be extracted from the original time series. Furthermore, the resulting data often display non-stationary patterns, with past observations influencing future ones. Therefore, sophisticated econometric techniques are required to obtain reliable estimates.

2.3 The decarbonization of "hard-to-abate" sectors

The data and commentary for this research was developed and provided by Frost & Sullivan and draws largely on edited content from its proprietary database of published Market and Technology research reports (accessible at www.frost.com). These are drafted by dedicated analysts who leveraged Frost & Sullivan's previous coverage and industry experience combined with a comprehensive program of desk-based and primary research. Secondary sources consulted include company websites, reports and press releases. Interviews were conducted with senior representatives across functions of direct and indirect market participants whose inputs are anonymized. This research is based on Frost & Sullivan's TechVision, Energy & Power Systems and Mega Trends practices.

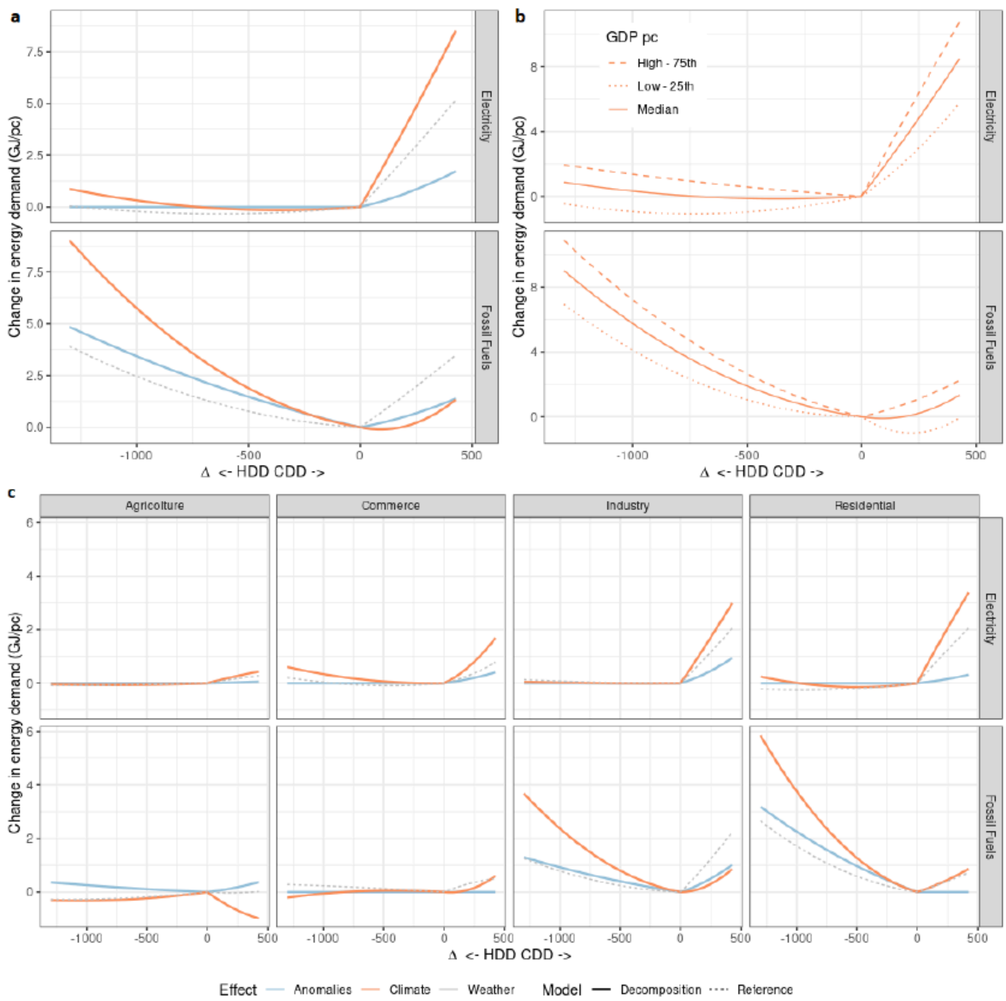
3. Research output

3.1 Climate-induced impacts on energy demand and supply

3.1.1.Energy demand functions

The empirical results support the hypothesis that consumers respond to average weather conditions over many years via new technology adoption or the adjustment of stocks of appliances with varying energy efficiencies. Overall, this points to an exacerbation of the sensitivity of electricity demand for cooling and fossil fuel demand for heating in the long run, since coefficients estimated from climatic variation are greater than those estimated exploiting idiosyncratic weather anomalies. Inspecting sector-specific shocks, we find evidence of adaptation - i.e. of a difference between short-and long-run shocks - as for electricity consumption in response to hot exposure across all sectors, for industrial and residential fossil fuel consumption in response to cold exposure and, to a lesser extent, for fossil fuel consumption in response to exposure to heat in the residential and commercial sector. We find evidence of a significant and large amplification effect of per capita income on the electricity and fossil demand response to heat and cold exposure (see 1, Panel b).

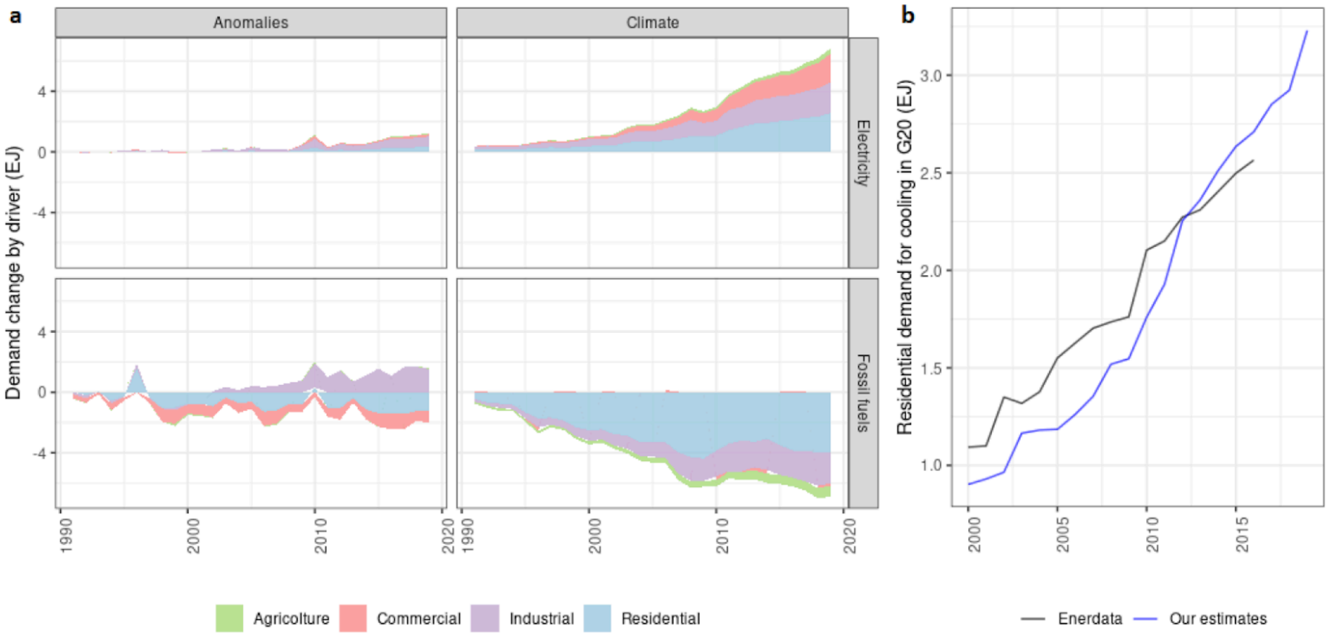
Figure 1: Estimated change on per capita energy demand (GJ/pc), total (panels a-b) and by sector (panel c), for electricity and fossil fuels. Total demand is computed by summing up the sector-specific demand shocks. Total demand changes due to climatic shifts are presented both at the median of per capita income (panel a), and at high (75th quantile) and low (25th quantile) levels of per capita income (panel b). Estimates based on climate exposure and weather anomalies (respectively orange and blue), are presented for positive variations in HDDs and CDDs of up to one standard deviation from their mean levels. The estimates of a reference model where climate and anomalies are not separated, so weather exposure is exploited for identification, are plotted as gray dashed lines.



3.1.2 Simulation of historical demand for cooling and heating

We identify the energy consumption attributable to climatic changes and weather anomalies in the historical record (1990-2019), taking as reference the average climatic conditions in the 1970-1989 period. Globally and across all sectors, the cumulative additional energy consumption that can be attributed to climatic changes in the 1990-2020 period amounts to 74 EJ for electricity and -125 EJ for fossil fuels. Idiosyncratic variations in weather on top of climatic changes accounted for an additional +10 EJ and -21 EJ, respectively. Electricity demand as a response to weather anomalies has become more important, with average annual changes of around 15% of the total additional electricity in demand in the 2015-2019 period.

Figure 2: Simulated variation in energy demand due to weather anomalies and climatic change in the historical period (1990-2019).

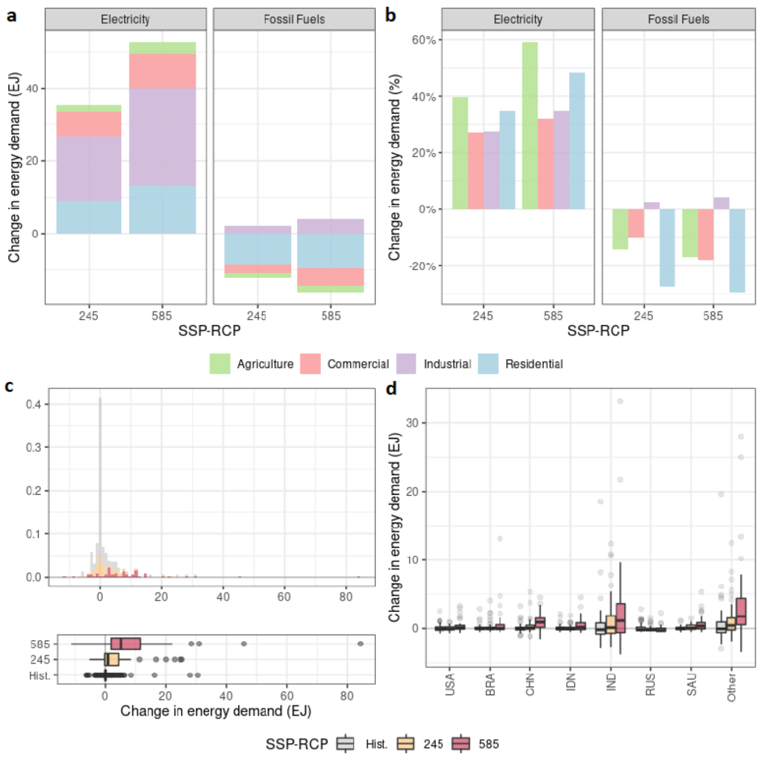


3.1.3 Simulation of future demand for cooling and heating

The second stage of our analysis combines the estimated response functions with climate change projections to estimate the impacts of mid-century temperature increases on electricity and fossil fuel demand, according to the future level of per capita income. We use representative 20-year periods from past (1996-2014) and future (2040-2059) epochs in 7 models. Energy demand is significantly amplified around mid-century due to energy-intensive adaptation actions as a response to long-run climatic shifts. Overall, at the global level, the future additional demand due to unexpected weather anomalies at the 75th (and 90th percentile) of the distribution amounts to 4 EJ and 8 EJ (11 EJ and 20 EJ). We find that climate change amplifies the impact of future anomalies and that countries in tropical areas - particularly in India - tend to experience great uncertainty about electricity demand due to unexpectedly hotter conditions.

Figure 3: Panels a-b: Global projected change in sector energy demand in levels (Panel a) and in relative terms (Panel b) due to shifts in the climate around 2050 with respect to the historical climate, by sector and energy carrier. The multi-model median of 7 model runs is shown. Panels c-d: Distribution of the

change in total energy demand due to the effect of historical (grey) and future (orange and red) unexpected anomalies, with respect to the GCM-specific historical climate and average historical weather anomalies, globally (Panel c) and across major economies (Panel d). The data used to show the density and boxplots of Panels c-d is based on each combination of model runs (GCM and year around 2050).

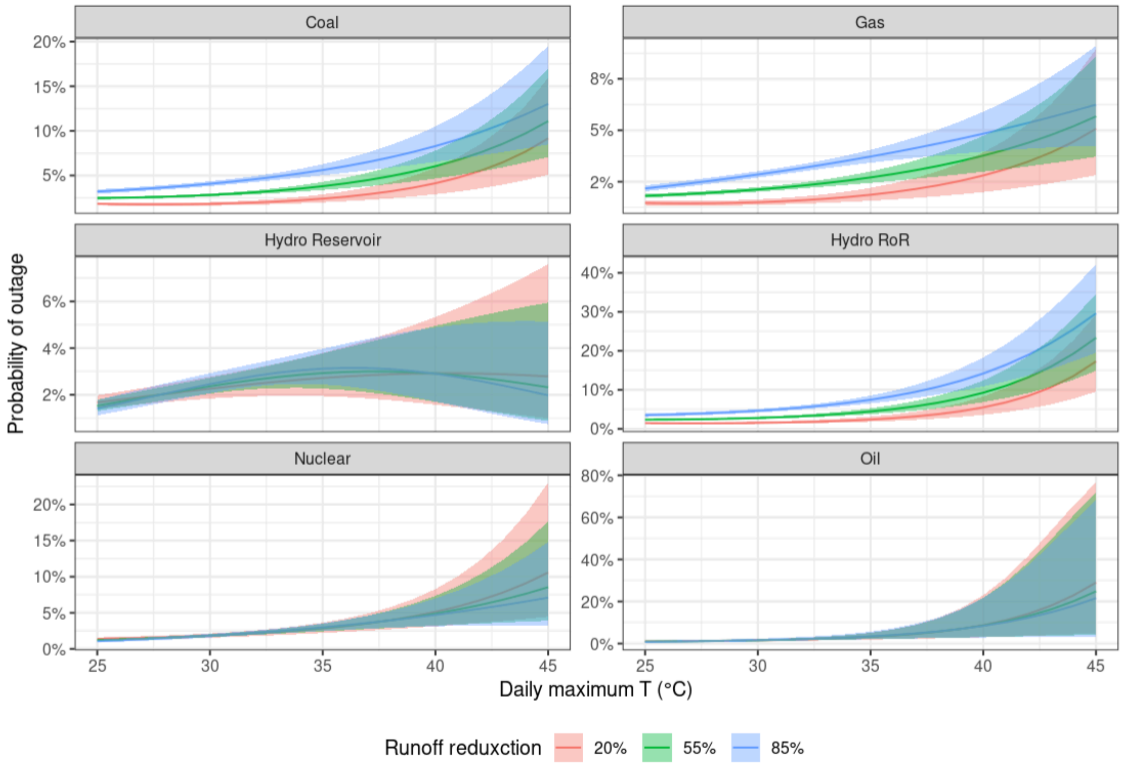


Overall, in Europe total demand combining all fuels and sectors declines by 1.7 EJ/year by 2050, due to the strong reduction in fossil fuel used in buildings from lower HDDs. Nevertheless, several European states experience a growth in electricity demand from 20-40% depending on the sector.

3.1.4 Energy Supply

We consider as a key dependent variable the occurrence of an outage in each power plant and identify the influence of daily maximum temperatures and water runoff anomalies. We find that coal power plants are the most vulnerable to outages, while gas is the most resilient. For hydropower generation, plants based on run-of-river are the most affected by low runoff and high temperatures (the probability of outage ranges between 20% and 40% within the 95th confidence interval).

Figure 4: Estimated response function of outage probability depending on maximum daily temperatures and water runoff anomalies.



3.2 Energy mix and emission factors: a local approach

From current national calculations, we identified new potential zonal and sub-zonal aggregations for local energy markets: this approach is in line with the aim of the European Union for an increasingly decentralized electricity market management and for a higher involvement of consumers, prosumers and local producers. AEF and MEF can be calculated at different levels and they provide us with information both regarding both the existing energy mix in specific areas and potential future developments, also coupling data from local energy production and changes in energy demand. The output of the research is an analysis of the current situation and its potential developments with varying installations and demand patterns, or holding stable one of the two.

The work is based on a detailed dataset on electricity production, installed capacity and related emissions: this output will be included in the platform to be opened for future and further research to make informed decisions while building local electricity markets.

3.3 The decarbonization of "hard-to-abate" sectors

Focusing on direct emissions, there are three main approaches to decarbonizing heavy industries: material modification, process innovation and emission management.

In the Oil & Gas (O&G) sector, the direct and indirect impacts of refining, transport, flaring, extraction and use mean the industry contributes about 15% to global emissions. In the O&G sector, material modification includes integrating renewables and process innovation covers co-generation while emission management includes reducing leaks. Indeed, leak detection and repair is amongst the most efficient approaches to abatement and has the potential to reduce emissions by 85%. More broadly, the O&G Climate Initiative, which represents about 33% of global production, has set ambitious abatement targets. For indirect emissions, future fuel use in the O&G industry currently remains limited but implementing new Carbon Capture, Utilization and Storage (CCUS) for hydrogen production offers a route to decarbonize. "Blue" hydrogen is produced from fossil fuels such as oil, gas and coal principally via steam methane or auto-thermal reforming. In parallel, "pink" hydrogen – generated from nuclear power – promises to be a motor for the increased adoption of H2. In the longer term, "green" hydrogen is attracting significant public sector support as a means to guarantee energy sustainability. Today, this accounts for only 0.1% of global production but has the potential to meet 24% of the world's energy demand through an additional $160 billion in financing. In Europe, the sector stands to benefit from the development and implementation of long-term clean energy strategies nationally and internationally.

There is an urgent need for abatement in hard-to-decarbonize heavy industries beyond oil & gas. In the cement industry, the average CO2 per ton of production has fallen drastically since the 1990s but still contributes about 6% to global emissions. In this sector, CCUS and novel materials have the highest potential. In the steel industry, decarbonization has not received any focused investment although the sector contributes approximately 7 -9% to global emissions. Material modification includes leveraging co-products, process innovation directly reduces iron while emission management also incorporates CCUS. In the short term, increased recycling and energy efficiency improvements are the most accessible and widely adopted CO2 abatement strategies in the steel industry but electrolysis for iron ore reduction is gaining interest for the long term. If other approaches to decarbonization fail or are unavailable, carbon offsetting provides market participants with another way to reduce their footprints. This strategy is supported in heavy industries by emerging digital solutions.

4. Policy implications

4.1 Climate-induced impacts on energy demand and supply

We find that coefficients estimated from changes in climatic exposure are larger than those estimated from idiosyncratic changes in weather. This result supports the hypothesis that consumers respond to average weather conditions over many years via new technology adoption or the adjustment of stocks of appliances with varying energy efficiencies. The implications of our methodological advance are broad-ranging because energy and income growth are symptomatic of a broader class of economic impacts of climate change, all of which have similar structures and might suffer from misattribution if damage functions estimated over short-term weather changes are used to infer the impacts of long-term climate change.

As for energy demand, our results underscore the importance of accounting for the further increase in demand due to short-term anomalies on top of long-run climate change to calculate its true potential costs.
Our demand-side analysis suggests that climate and weather anomaly-driven electricity demand must be accommodated by ramp-up requirements on power generating units. If such power requirements cannot be met through variable renewable sources, power systems must ramp up flexible generation technologies, typically gas and coal-fired generation, with important implications on the emissions of GHG and local air pollutants. In addition, our results for power supply availability underscore that, during extreme weather conditions, coal, gas, and run-of-river hydropower generation can experience an increase in the risk of unexpected power outages. Our research demonstrates the need for new analyses of the influence of power supply-side shocks on power systems for planning generation.

4.2 Energy mix and emission factors: a local approach

MEFs can be used to incentivize the development and deployment of renewable energy sources. Policymakers can offer financial incentives, subsidies or tax credits to encourage the adoption of low-carbon electricity generation technologies such as wind, solar, and hydropower. By making these technologies more economically competitive, MEFs help to reduce the reliance on fossil fuels. Governments can use MEFs

to set carbon prices, such as carbon taxes or emissions trading system allowances, specifically targeting electricity generation.
MEFs inform the setting of emissions standards and regulations for power plants.
In electricity markets, by introducing capacity markets or electricity pricing structures that reward power plants with lower emissions, MEFs can be used to encourage cleaner generation.
MEFs can guide efforts to decarbonize the electricity grid: policymakers can set targets for reducing the carbon intensity of electricity generation over time and implement policies to retire coal-fired power plants, increase the share of renewables and improve grid efficiency.
MEFs help to prioritize investments in grid infrastructure. Policymakers can direct resources toward upgrading transmission and distribution systems in regions with high-emission electricity sources to facilitate the integration of cleaner energy.
Information on the carbon intensity of electricity generation can empower consumers to make more sustainable choices and influences their energy consumption behavior.
MEFs are essential for international agreements and collaboration related to electricity generation emissions reduction targets.
To summarize, estimating marginal emission factors for electricity generation is a critical step in crafting effective energy and environmental policies.

4.3 The decarbonization of “hard-to-abate” sectors

Energy systems and hard-to-abate sectors need to integrate low- and zero-carbon technologies through the interchange of different technologies. Transitioning to low-carbon production processes requires the deployment of clean energy technologies, new infrastructures and new green fuels (e.g. green hydrogen). The energy transition is also key both to tackling climate change and to reaching a higher degree of energy independence. Following volatility in international energy market prices and the Russia-Ukraine war, exacerbating the energy crisis, energy independence has become a matter of great urgency.

To achieve carbon neutrality, action is needed to maximize the use of these technologies. Hence, efforts are needed to identify the proper technology interplay by raising awareness, developing policy frameworks and financing a fair transition toward carbon-neutral energy systems. Beyond specific policies to ensure an efficient and effective decarbonization pathway to 2050, it is essential to define key prerequisites or enabling factors to guarantee optimum investment conditions for companies and end users. On the one hand, companies need to operate in a well-defined legislative context. On the other, public support should be provided for industrial production in scaling up existing green technologies, developing and adopting new green solutions and ending fossil fuel subsidies. This becomes even more urgent in the light of the ambitious targets set out in Europe, notably the "Fit for 55" package, and the guidelines included in the "REPowerEU" plan.

The EU, and in particular Italy, has not fully developed complete and integrated supply chains for several green technologies considered key to the energy transition. Indeed, to be in line with decarbonization pathways, it is necessary to build a European industrial strategy and a resilient raw materials supply chain, continuing to promote initiatives such as the European Raw Materials Alliance, European Battery Alliance and European Hydrogen Alliance. We believe that the insights represented in this study could be useful both for companies in those sectors and for policymakers.

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