October 2021

Fondazione Eni Enrico Mattei

Working Paper

024.2021

Towards the decarbonization of the power sector – a comparison of China, the EU and the US based on historical data

Michel Noussan, Manfred Hafner, Loyle Campbell, Xinqing Lu, Pier Paolo Raimondi, Erpu Zhu

Towards the decarbonization of the power sector – a comparison of China, the EU and the US based on historical data

By Michel Noussan, Fondazione Eni Enrico Mattei, SciencesPo – Paris School of International Affairs
Manfred Hafner, Fondazione Eni Enrico Mattei, SciencesPo – Paris School of International Affairs, Johns Hopkins University – School of Advanced International Studies
Loyle Campbell, SciencesPo – Paris School of International Affairs
Xinging Lu, SciencesPo – Paris School of International Affairs
Pier Paolo Raimondi, Fondazione Eni Enrico Mattei, Istituto Affarti Internazionali
Erpu Zhu, SciencesPo – Paris School of International Affairs

Summary

This work compares the different decarbonization strategies of the power sector in China, the European Union and the United States, by considering the historical evolution of electricity generation and the current situation. Such a comparison is gaining a broader significance when evaluated with an additional level of geographic detail, by comparing European countries, Chinese provinces, and US states. The differences among these geographies highlight the challenges and opportunities of pushing towards low-carbon technologies, by making clear that regional decarbonization will need to address very different local contexts. Moreover, multiple policy and planning levels are involved, and those mechanisms are different in the three blocs being compared. Our analysis shows that these three blocs, although moving towards similar decarbonization targets, are currently at different levels of carbon intensity. The zero-carbon pathway will need to be declined in different local goals, based on the availability of low-carbon resources and the electricity demand. Given the geographical differences between demand and supply, and the likely increase of electricity demand, an improvement of power transmission networks will be essential. This work is part of a series of papers on the geopolitics of the energy transition in China, the European Union and the United States of America.

Keywords: Electricity, Power, Decarbonization, Energy Transition, China, EU, US

JEL Classification: N70, O13, P48, Q42

Address for correspondence:
Michel Noussan
SciencesPo – Paris School of International Affairs
Rue des Saints-Pères, 28
75007 Paris
France
E-mail: michel.noussan@sciencespo.fr

Towards the decarbonization of the power sector – a comparison of China, the EU and the US based on historical data

Michel Noussan [a,b,], Manfred Hafner [a,b,c], Loyle Campbell [b], Xinqing Lu [b], Pier Paolo Raimondi [a,d], Erpu Zhu [b]*

[a] Fondazione Eni Enrico Mattei, Milano, Italy

[b] SciencesPo - Paris School of International Affairs (PSIA), Paris, France

[c] Johns Hopkins University - School of Advanced International Studies (SAIS-Europe), Bologna, Italy

[d] Istituto Affari Internazionali, Roma, Italy

** corresponding author: michel.noussan@sciencespo.fr*

Abstract

This work compares the different decarbonization strategies of the power sector in China, the European Union and the United States, by considering the historical evolution of electricity generation and the current situation. Such a comparison is gaining a broader significance when evaluated with an additional level of geographic detail, by comparing European countries, Chinese provinces, and US states. The differences among these geographies highlight the challenges and opportunities of pushing towards low-carbon technologies, by making clear that regional decarbonization will need to address very different local contexts. Moreover, multiple policy and planning levels are involved, and those mechanisms are different in the three blocs being compared. Our analysis shows that these three blocs, although moving towards similar decarbonization targets, are currently at different levels of carbon intensity. The zero-carbon pathway will need to be declined in different local goals, based on the availability of low-carbon resources and the electricity demand. Given the geographical differences between demand and supply, and the likely increase of electricity demand, an improvement of power transmission networks will be essential. This work is part of a series of papers on the geopolitics of the energy transition in China, the European Union and the United States of America.

Keywords: electricity, power, decarbonization, energy transition, China, EU, US

JEL Classification: N70, O13, P48, Q42

1. Introduction

Many countries worldwide are deploying strategies to decarbonize their energy and economic systems, supporting an energy transition from the current fossil-based systems towards low-carbon alternatives. A key pillar of these strategies is often the power sector, since the supply of low-carbon energy to the final users is easier when it is supplied as electricity. Thus, much emphasis is placed on technologies that increase electricity consumption in buildings, industry, and transport, such as electric vehicles and heat pumps. The share of electricity in final energy consumption at global level has already increased from 15.5% in 2000 to 19.4% in 2018, and this trend is expected to continue to 28% in 2040, according to IEA's Sustainable Development Scenario[1] [1].

However, although electrification could bring many advantages for final users, to effectively decarbonize the energy system it needs to be coupled with clean electricity generation. The global share of low-carbon power generation started to increase in 2012, after years of decline caused by decreasing nuclear power generation. Global low-carbon electricity was 39% in 2020, up from 32% in 2011, and such an increase was mainly driven by wind and solar power [2]. However, while the emission factor of electricity is decreasing, the total CO_2 emissions of the sector are continuously rising, due to the net increase of electricity consumption (with a 25% increase of global consumption in the last decade). Again, a holistic perspective is required, since specific indicators are important to define targets and strategies, but the whole picture should be the final aim of any decarbonization strategy.

Decarbonization strategies are being deployed by different countries, mostly towards a net-zero energy system by 2050, and in some cases by 2060 (including China). However, these strategies still lack comprehensive and practical roadmaps that define the actions and tools needed to reach these targets. The three largest economies aiming at net-zero are China, the EU and the US [3]. Together they are responsible for around 40% of today's carbon emissions, and given their central role in this challenging path, their choice of cooperating or competing will have significant effect on the outcome of these efforts. While other countries will also represent a remarkable share of emissions (particularly India, Russia, Middle East countries, etc.), all these three blocs are aiming to acquire a position of global leadership on climate change and the energy transition.

[1] The IEA's Sustainable Development Scenario, which is fully aligned with the Paris Agreement, represents a future evolution towards a decarbonized energy system.

This paper presents a comparison of the power sector in the three major blocs proposing decarbonization strategies, with the aim of analyzing the features of power generation at different administrative levels. While country-level comparisons are abundant, each large economy shows significant variability across internal administrative units. This highlights the importance of developing various strategies based on the characteristics of each region in terms of electricity consumption and supply, as well as on the available infrastructure for transmission across regions.

A synthesis of some indicators to compare these three blocs is reported in Table 1.

Table 1 – Main features of the three economies considered in this analysis.

		China	**European Union**	**United States**
high-level admin. unit	*type*	Country	Union of countries	Country
Total population[2]	*million (2019)*	1,398	448	328
Total GDP[3]	*billion USD (2019)*	14,280	15,626	21,433
Total GDP PPP[4]	*billion int. $ (2019)*	23,444	20,793	21,433
GDP PPP per capita	*int. $/cap (2019)*	16,770	46,413	65,345
Power generation[5]	*TWh (2019)*	7,519	2,912	4,391
Power generation per capita	*kWh/cap*	5,378	6,500	13,387
medium-level admin. units	*type*	Provinces	Countries	States
number	-	31*	27**	50***
population (max)	*million (2019)*	115.2	83.2	39.5
population (median)	*million (2019)*	38.8	8.9	4.3
population (min)	*million (2019)*	3.5	0.5	0.6
GDP PPP[6] (max)	*billion int. $ (2019)*	2,632	3,594	3,133
GDP PPP (median)	*billion int. $ (2019)*	597	258	255
GDP PPP (min)	*billion int. $ (2019)*	45	19	34
GDP PPP per capita (max)	*int. $/cap (2019)*	39,186	108,951	90,043
GDP PPP per capita (median)	*int. $/cap (2019)*	13,802	41,407	60,445
GDP PPP per capita (min)	*int. $/cap (2019)*	8,564	24,595	40,464

** Excluding the 2 Special Administrative Regions (Hong Kong and Macau) and 1 disputed region (Taiwan). ** The European Union considered in this study is the EU-27, after the withdrawal of the United Kingdom (UK) on Jan 31st, 2020. *** Excluding District of Columbia.*

[2] World Bank Data, Total population, https://data.worldbank.org/indicator/SP.POP.TOTL
[3] World Bank Data, Nominal GDP, https://data.worldbank.org/indicator/NY.GDP.MKTP.CD
[4] World Bank Data, GDP, PPP, https://data.worldbank.org/indicator/NY.GDP.MKTP.PP.CD
[5] Source: ENERDATA (2021).
[6] Sources: https://data.stats.gov.cn/english/easyquery.htm?cn=E0103 (with 1 USD = 6.91 CNY), https://ec.europa.eu/eurostat/databrowser/view/tec00001/default/table?lang=en (with 1 Euro = 1.12 int $), https://apps.bea.gov/itable/iTable.cfm?ReqID=70&step=1&acrdn=1

While these three blocs are often considered as the main players for energy systems decarbonization, it is important to be aware of the differences among them. Although the US and the EU-27 still have a larger GDP than China, China's population is almost two times the combined population of the US and EU-27. The increasing quality of life for Chinese citizens will likely drive an increase in both GDP and total electricity demand in the country, which will make it even harder to decarbonize the sector. Additional differences arise when considering the medium-level administrative units, which are Chinese provinces[7], EU countries and US states. These units show a significant variability in terms of population, GDP and power generation, which is noticeable in all the three blocs. For this reason, we argue that it is important to discuss this variability, as an affordable and effective decarbonization strategy for the power sector needs to build on the specific opportunities of each geography, while average figures often hide more complex constraints and opportunities at a local level.

This work is the first of a series of papers on the geopolitics of the energy transition in China, the European Union and the United States of America. Other upcoming papers will deal with energy and climate governance, energy security and rare earth materials.

2. Decarbonization strategies

The three economic blocs that are considered in this paper have already set clear decarbonization targets to reach a net-zero energy system either by 2050 or 2060. The EU was the first bloc to propose a target on carbon neutrality, with the European Commission setting a vision for a carbon-neutral EU in November 2018 [4]. The second large bloc to announce a path towards carbon neutrality was China. In September 2020, President Xi Jinping declared that China will aim to hit peak emissions before 2030 and for carbon neutrality by 2060 [5]. Conversely, the US rolled back climate change and related energy policies under the Trump administration, but things have changed with the election of President Biden in 2020: the US has re-joined the Paris Agreement, and set a target of a net-zero emissions economy by 2050 [6]. Moreover, the US is also aiming at reaching zero-carbon power generation by 2035. However, this target seems particularly challenging given the current situation of the power sector in the US [7]. Notable barriers include the recent shift from coal to natural gas, the partisan politicization of climate science, the low

[7] We would like to remark that the term "provinces" in this paper refers to provincial-level administrative regions, including both provinces and autonomous regions. We have chosen to use "provinces" to simplify the wording, especially in charts.

maturity of CCS plants, the role of nuclear, and the limited availability of interstate transmission grids to connect areas with renewable potential to others with high electricity demand.

2.1. China

The announcement of President Xi Jinping at the UN General Assembly in September 2020 about the intention to “have CO_2 emissions peak before 2030 and achieve carbon neutrality before 2060” is one of the most important targets for combatting climate change worldwide. This net zero ambition can also bring economic advantages, as it could help China boost its GDP by 5% in this decade [8]. The global share of carbon emissions by China is significant (28% of global CO_2 emissions in 2019), and the decarbonization of the Chinese power sector, mostly based on coal, represents an important challenge.

The Chinese government's 14th five-year plan, presented in March 2021, has been much-anticipated as the moment the country would consolidate its 2060 commitment, and update its promise to achieve peak carbon emissions before 2030 [9]. However, the plan only mentioned targets of energy efficiency, such as “Reduction in energy consumption per unit of GDP (%)” and “Reduction of CO2 emissions per unit of GDP (%)”, but did not mention total emission cap, or any detailed decarbonisation pathway scenarios. Energy and electricity sector specific planning is expected to be announced in Q4 2021. Also, the nationally determined contribution (NDC) target as part of the Paris climate deal has not been updated (although it is expected soon). Still, the five-year plan included some positive indications, such as raising the share of non-fossil fuel sources in China's energy mix from 15% in the previous plan to around 20% for 2021-25, and the commitment to build 1200 GW of wind and solar capacity by 2025.

In addition to the top-down policies deployed at the national level, provinces and municipalities in China have adopted a number of measures on climate change mitigations [10]. Local governments have set targets and developed plans for the reduction of carbon intensity, in some cases with specific disaggregated targets to cities and counties. Local communities have launched several low-carbon pilot projects, and 73 provinces and municipalities have set target dates for reaching peak greenhouse-gas emissions. Other examples include the introduction of pilot emission-trading systems, new subsidies to promote switching from coal to natural gas in rural areas, and incentives for low-emission vehicles.

The large autonomy granted to lower levels of government is an opportunity to tackle climate change, but it requires also an effective coordination to reach specific goals at the national level. In the current situation, the prioritization of climate goals is not uniform across governmental agencies, and gaps in the overall institutional framework persist [11]. However, China has developed a low-carbon-development policy system that spans to several jurisdictional levels, involving various regions and industries. Different case studies in China demonstrated that similar policy options may achieve different results at different times, depending on the province's or city's stage of industrial development [12]. The central government has worked to strengthen policy implementation by covering a large share of their costs and by increasing resources for monitoring and enforcement at the local level. China has recently established a formal working group on carbon emissions statistics and accounting, led by the National Development and Reform Commission and the National Bureau of Statistics. This will put China's decarbonisation under more scientific guidance in statistical terms. However, local governments continue to face constraints in environmental enforcement, caused by the greater restrictions on borrowing by local governments and reduced local revenue flows due to other policies and macroeconomic changes. Another key constraint is that the key performance indicator for provincial and municipal government officials are still largely based on GDP, although environmental indicators have taken a more and more important place in the cadre evaluation system of the past years. Moreover, there is a declining fiscal support from the central government, as China adjusts to a "new normal" of slower overall growth [13].

One of the key tools to support decarbonization of the power sector is the emission trading system (ETS), which was launched in 2017 and started operating nationally in the Chinese power sector in 2021. By covering Chinese coal and gas power plants, it represents the world's largest ETS scheme. This market-based tool can represent an important opportunity to decrease the emissions of the Chinese power sector, by gradually tightening the emission benchmarks to support the peak of the power sector's emissions well before 2030. Moreover, it is important that its deployment is coordinated with other measures, including energy efficiency, renewables deployment and CCUS support policies [14].

It is important to highlight that before the implementation of a national ETS, seven pilot projects of local ETSs have been operating in China since 2013. Now that China is pushing for a national system, the evolution of these local schemes remains an open question [15]. The full integration of these systems may be the most efficient option, while presenting several challenges. Unified rules will be required, together with a clear transition plan, and local authorities will lose control on their schemes. Attention should be directed toward strengthening and harmonizing guidelines for measurement, reporting, and verification in existing systems, and lessons learned from local schemes can become a useful input for the organization of an effective national ETS.

2.2. European Union

The European Union already has well defined energy and climate targets, starting from the 2020 climate & energy package back in 2007. The EU leaders set three distinct targets to be reached by 2020: (1) 20% cut in greenhouse gas emissions (from 1990 levels), (2) 20% of EU final energy consumption from renewables, (3) 20% improvement in energy efficiency compared to a baseline. These goals, to be reached at the EU level, were then distributed in different national targets for each Member State.

EU countries have agreed on binding annual targets until 2020 for cutting emissions in some sectors that are not part of the EU ETS (accounting for 60% of EU emissions), under the "effort sharing decision". The national targets were based on the countries' wealth: emissions variations ranged from a 20% cut for the richest countries to a maximum 20% increase for the least wealthy by 2020 (leading to an overall 10% emission cut from 2005 to 2020), although they were still projected to have to make efforts to limit emissions increases to these levels. Each country was requested to report its emissions yearly, with the Commission monitoring the progress towards the goals.

A similar agreement has been set on national renewable targets, focused on the share of renewable energy in final energy consumption (divided into electricity, heating and cooling, and transport). These targets and the calculation and monitoring rules were set in the Renewable Energy Directive, published in 2009. Also in this case each national target was different, with the aim of reflecting different starting points for renewable energy production and the ability of each country to increase it (from 10% in Malta to 49% in Sweden). The overall effect aimed at reaching a 20% target for the EU (doubling the 2010 level of 9.8%), as well as a specific target of 10% in the transport sector.

The 2020 targets were updated to reach a 40% cut in GHG emissions, a 32% share of renewable energy and a 32.5% improvement on energy efficiency by 2030. However, after the global COVID pandemic, a higher climate ambition was proposed through the framework of the European Green Deal[8] in September 2020. This revision aims to reduce 2030 emissions by 55% compared to 1990 levels. In parallel to this, other targets are being updated accordingly. Again, the national targets on emission cuts will be defined in the Effort Sharing legislation (for the sectors that are not covered by the EU ETS), and the Member States are responsible for developing the national

[8] The European Green Deal is a set of policy measures developed by the European Commission with the main objective of reaching a climate-neutral EU by 2050.

policies and measures needed to reach these targets. Some EU measures may also help in reaching these targets, such as the CO_2 emission standards for new cars and vans.

In July 2021, the European Commission released its 'Fit for 55' package, which aims at facilitating the European Union emission reduction of 55% by 2030 (compared to the 1990 level). Some of the numerous legislative proposals are a evolution and expansion of existing climate and energy policies. For example, the package proposes to increase the share renewable energy of total energy consumption from at least 32% to 40% by 2030.

At the current stage, no clear targets have been set for decarbonizing the power sector. EU countries show very variable energy mixes, as we will describe in this work, and also different priorities are given towards various low-carbon sources. The role of nuclear will likely become a crucial point of discussion in future strategies. Some countries are strongly relying on this low-carbon source (up to 70% of power generation in France and 39% Sweden in 2019, and other smaller countries with large shares), while others have already phased-out nuclear energy from their electricity mixes (including Italy some decades ago and Germany recently). It must also be mentioned that in the EU, the power mix (and therefore inclusion or not of nuclear in the mix) is a prerogative of the Member States and not of the European Commission.

Although the European Union has demonstrated its ability to reach consensus across member states on climate targets, the path ahead will be particularly challenging, due to the amount of emission cuts and investments that will be required. Also, the fact that energy is a "shared competence" between national governments and European institutions contributes to the heterogeneous nature of European energy landscape. Indeed, energy has always been considered a strategic issue, and Member States were not keen to leave such a strategic topic exclusively to the EU responsibility. The differences across countries, especially when considering the average wealth and income, represent a barrier towards effective implementation of the solutions required to reach a carbon-neutral economy by mid-century. Although climate policies have been linked to the EU's COVID-19 Recovery Fund, the choices of national governments will be a key aspect for the deployment of effective and coherent solutions across the region.

2.3. United States

In the last years, climate laws and regulations in the United States have seen a significant evolution both at the federal and local levels. The most notorious moment was the choice of the Trump Administration to withdraw from the Paris Agreement, as declared on June 1st, 2017. As a result, a small group of governors and majors formed the US Climate Alliance, with the aim of committing to reach the agreements targets by forming a coalition between states, localities, tribes, and private/public/non-governmental actors. Since then, the Alliance has included multiple and bipartisan states, reaching 61% of the US economy, 57% of its population and 43% of its emissions [16]. However, the new Biden Administration has reversed the Trump Administration's withdrawal of the Paris Agreement at a federal level, re-joining the Accord and using the Build Back Better Plan as a foundation for strong mid-century decarbonization goals (and a net-zero power generation by 2035). Reaching such targets will however require a range of federal and local policies, that need to reach a bipartisan consensus to make sure that climate policies being put forward are durable and not reversed in subsequent administrations. In addition, significant investment will be required in power grid infrastructure, to fill the gap caused by decades of neglected investments.

An important aspect remains the coordination between policies implemented at the federal level with those developed at the state and local levels [17]. Subnational policies to tackle climate change appear to be particularly desirable when there is no action at national level, or such action is perceived as ineffective. Although the most cost-efficient way of tackling climate change remains at the national level, with a strong coordination at the global level, in some cases sub-national policies can help in reaching the national targets. The US experience in the last years demonstrated that the interaction between policies at the federal level and at the state and local level can be either positive or negative, depending on a range of factors [17]. Problematic results emerge when in the presence of a national standard (e.g. limit on emissions) some states develop more stringent rules, leading the other states to lessen their efforts. Such an outcome results in a carbon leakage and a loss in cost-effectiveness at the national level. Excluding these states from the federal policy could limit the leakage, but the effectiveness of the measure would remain sub-optimal. In other cases, the proactive role of local communities can push the federal government towards more stringent measures, in some cases also by developing laboratories or pilot and demonstration projects in specific contexts (as already discussed above for some Chinese provinces and cities). Examples exist in the recent American history of state-level policies that pushed for more stringent federal regulations, such as the US Clean Air Act, or the federal CAFE standards on the energy consumption of vehicles that have been tightened thanks to the more stringent standards in California.

Moreover, while both the EU and China have proven to provide a consistent support for climate policies over time, in the US climate change remains a partisan issue, supported by Democrats and dismissed by Republicans [3]. This problem has significantly affected the federal level, with different governments supporting climate regulations at different pace. Although it is not trivial to change federal laws and regulations, the opposite approaches of the two largest US parties significantly affects the effectiveness of climate strategies. Also, this partisanship is also evident at the State level, resulting in very different approaches and policies across the US [18].

Different states with Democratic majorities have passed bills aiming at a 100% carbon-free electricity generation by mid-century (California, Colorado, Maine, Nevada, New Mexico, New York and Washington). Other Republican states, like Texas and Ohio, have avoided setting carbon emission limits to support the development of their oil and gas industry driven by the fracking boom. The potential effect of climate regulations on large industries and companies could be significant, with some states with stringent limits that risk seeing their industries moving towards other less strict states. Some mitigating measures exist, like a proper structuring of carbon pricing schemes that can still provide subsidies to industries that want to remain in the state.

This partisanship grew stronger during the Obama administration, and even more during the Trump administration, when global warming became more politically divisive. Before that time, some conservative states were passing renewable electricity mandates (Kansas and Ohio) or evaluating the possibility of reducing emissions (Minnesota and Indiana) [18]. This growing partisanship will likely represent the hardest barrier to overcome when aiming at a consistent and effective strategy to tackle carbon emissions at the federal level.

Among the three geo-economic blocks analysed here, the US is the only bloc where one of the two major governing parties is to a large extent climate policy hostile and with it an important part of the electorate. Taking into considerations that there are Presidential elections every four years and that different Administrations with opposite views related to climate policies may follow each other, and that even during the mandate of one Presidential Administration majorities in Congress often shift at mid-term elections, it seems that in the US it will be more difficult than elsewhere to have a coherent decarbonisation plan towards carbon neutrality by mid-century. In the EU for instance, not only there is a wide consensus about addressing climate change among most major parties and the the majority of the population, but climate policies are to a large extent inscribed in European law therefore rendering it impossible by national governments to change route in case of a newly appointed climate sceptical government. Also in China it seems safe to bet on a continuity to address climate change and therefore to strengthen the implementation of climate policies towards carbon neutrality, as these policies are dictated top down.

3. Comparison of historical trends

An analysis of the historical evolution of the power sector in these three economies can provide useful insights to understand the magnitude of the goals ahead. Although most of the past dynamics were not specifically related to clear climate goals, with the notable exception of the EU during the last two decades, they clearly show the slow rate of change of the electricity mix. Its variations are in fact related to the operation of a large number of power plants that have quite long technical lifetimes. This aspect is of particular importance when considering such rapid decarbonization targets for the next decades. Moreover, in addition to focusing on a country level (or EU level), it is sometimes important to also consider a lower level of administrative units, to assess the variability of electricity mixes often hidden behind average figures. For this reason, this work has been based on the analysis and comparison of the historical trends in Chinese provinces, EU countries and US states, to outline their contribution towards the decarbonization of the power system in these economies.

3.1. Methodology and input data

The analysis of the power sector across the three blocs and two layers of administrative units is based on historical data of electricity generation by source and specific emission factors. The characteristics of power generation at the country level have been widely addressed in the literature, and complete data is available with good historical coverage. Conversely, finding detailed and accurate data with a higher spatial detail is less trivial. For both China and the United States, the analysis of medium-level administrative units requires the analysis of data from different sources, mostly thanks to national statistic bureaux. Each source usually collects different types of data based on the specific choices of each country and may also have changed over the years. For instance, power generation by sources in Chinese provinces do not provide the detail on the different fuels used in thermoelectric power plants, while details on other sources such as hydropower or nuclear are available.

In this paper, power generation data is analysed with the same methodology at two different levels of administrative units, comparing the results across the three main economies that are considered. The three main indicators that are considered are:

- The electricity mix of power generation by source, defined as the share produced by each source over the total generation, considering nine main sources (coal, natural gas, oil products, nuclear, bioenergy, hydro, solar, wind and others);
- The CO_2 emission factor of electricity generation, only considering the direct emissions of the power plants;
- The balance between electricity demand and supply, which corresponds to the net export of power with the adjacent regions, by comparing electricity imports and exports.

The first two indicators are naturally linked, but while decarbonization strategies are often focused on electricity emission factors, the concrete actions required need to address the electricity mix. Additionally, absolute power generation by source is also considered, since it is important to remember that the information represented by the electricity mix should also be considered looking at the absolute variation of power generation and consumption. Finally, the third indicator allows us to shed additional light on the imbalances between demand and supply across regions, which is an additional aspect that is often neglected but which is crucial for an effective decarbonization strategy.

The electricity mix has been calculated based on the electricity generation by source, which is available for all the geographies considered in this study, although from different sources and with some slightly different details. The major one is the unavailability of the thermal generation by fuel in Chinese provinces. For this reason, the electricity mix in this case has not considered additional details on fossil fuels, based on the fact that coal generation represented always more than 90% of thermal generation in China in the last 20 years. Data at the country level were retrieved from Enerdata, while data on the US States was available from the EIA and data for China Provinces was published in the China Energy Statistic Yearbooks.

The CO_2 emission factor has been calculated in different ways depending on the available data. Figures at country level are already available as an indicator from Enerdata, without the need of additional elaborations. Emission factors for the states of the US have been calculated by dividing the total CO_2 emissions of the power sector, published by the EIA, by the total power generation. Unfortunately, no official data of CO_2 emissions for power generation are available for the Chinese provinces. Thus, the emission factor has been calculated by allocating to the provinces the average national emission factor of thermal power to the share of thermal power in each province.

This choice may cause some approximations, especially in provinces where there is a significant amount of natural gas use (such as Guangdong and Jiangsu). However, since its role remains marginal today in comparison with coal, given the lack of additional data we believe that such an approximation still provides acceptable and useful results.

The comparison between electricity demand and supply has been done by considering different data sources based on the level of detail that was available for any geography. For the high-level administrative units, and for the country-level in the EU, import and export data were available, and the indicator has been calculated from this information. Conversely, for Chinese provinces and American states the analysis has been performed using data on electricity generation and electricity consumption. A correction has been necessary for the US states, since the data on energy consumption was related to final users, without the inclusion of the losses, leading to final results that were not comparable with the other geographies. To overcome this issue, a correction has been done by estimating the electricity losses considering the data for Texas: given that Texas is the only continental US state that is not connected to any other, its total generation needs to compensate its total consumption. The median value of the losses that resulted from this calculation is around 17%, with a slight variation over the years. We believe that this approximation gives an acceptable result, given the lack of more precise data at a state level.

Most of the analysis has been developed in the R programming environment[9], using the packages included into the tidyverse[10].

3.2. Comparison on high-level administrative units

As discussed above, all the three economies considered in this work have committed to decarbonize their energy systems, including the power sector. It is useful to analyse the historical evolution of their electricity mix in the last decades, to put these strategies into perspective. Figure 1 represents the evolution of the electricity mix of these three regions over the last five decades.

Considering this historical perspective, coal remained the first energy source for the large majority of years on record in the three regions. In fact, coal still represents 65% of electricity generation in China in 2019, although its share is lower than the historical peak of 81% in 2007. Coal also remained the first source in the EU-27 until 1997 (when it has been overtaken by nuclear) and in

[9] R Core Team (2020). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.
[10] Wickham H, et al. (2019). "Welcome to the tidyverse." Journal of Open Source Software, 4(43), 1686. doi: 10.21105/joss.01686.

the United States until 2016, when natural gas took the lead. These last two regions currently show a more balanced mix than China, which is strongly relying on coal and hydro. In all the economies wind and solar increased strongly in the last decade, although they still remain marginal, reaching a combined share of 12% only in the EU-27.

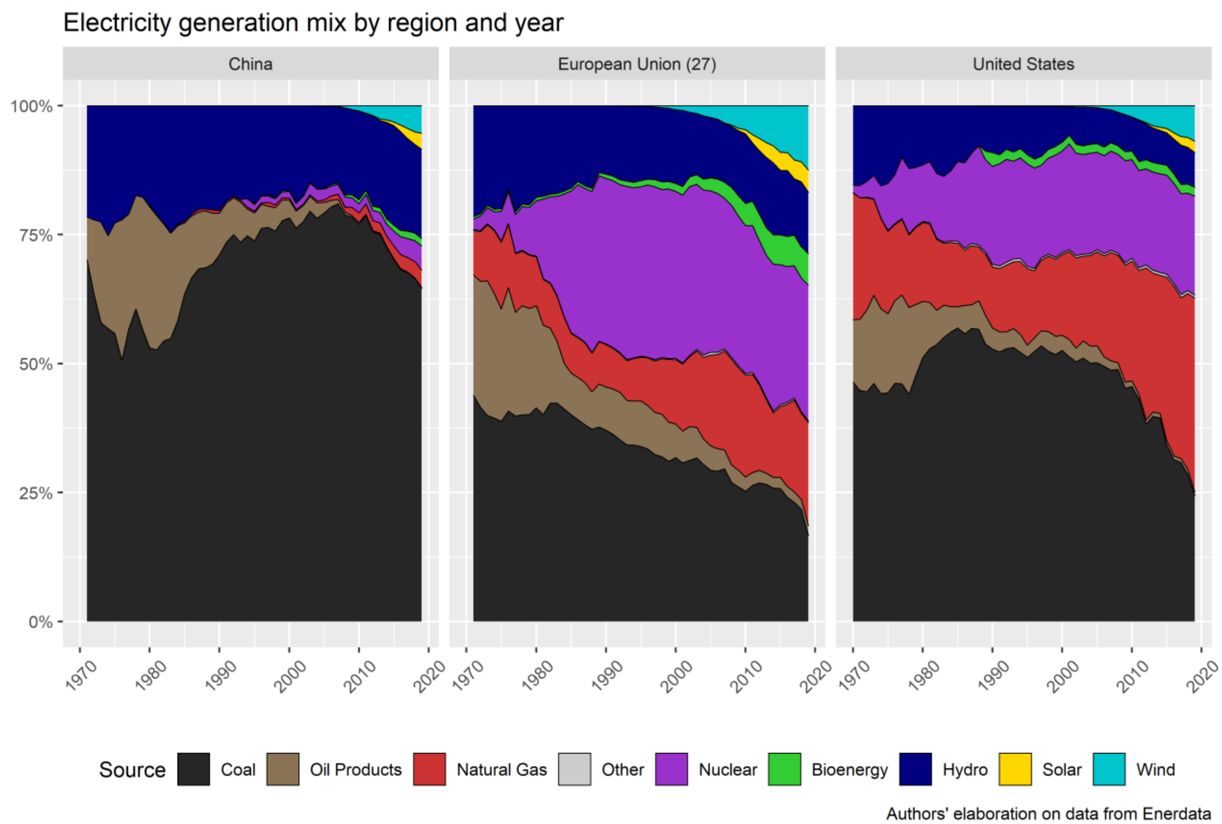

Figure 1 – Electricity generation mix by region and year, 1971-2019 (Authors' elaboration on data from Enerdata).

While the comparison of the electricity mix is an important analysis, it is also necessary to remember the absolute figures related to power generation, reported in Figure 2. While in the US and the EU-27 the total power generation (and thus consumption) seems to have reached a plateau in the last decade, China shows a dramatically increasing trend, which may well continue in the future. While the relative share of power generation from coal has decreased, as discussed above, the absolute value is continuing to increase, and so are the total emissions associated to it. This example shows that any comparison and analysis of future trends need to tackle simultaneously these two perspectives, since they both involve important aspects for policies aiming at decarbonizing the power sector.

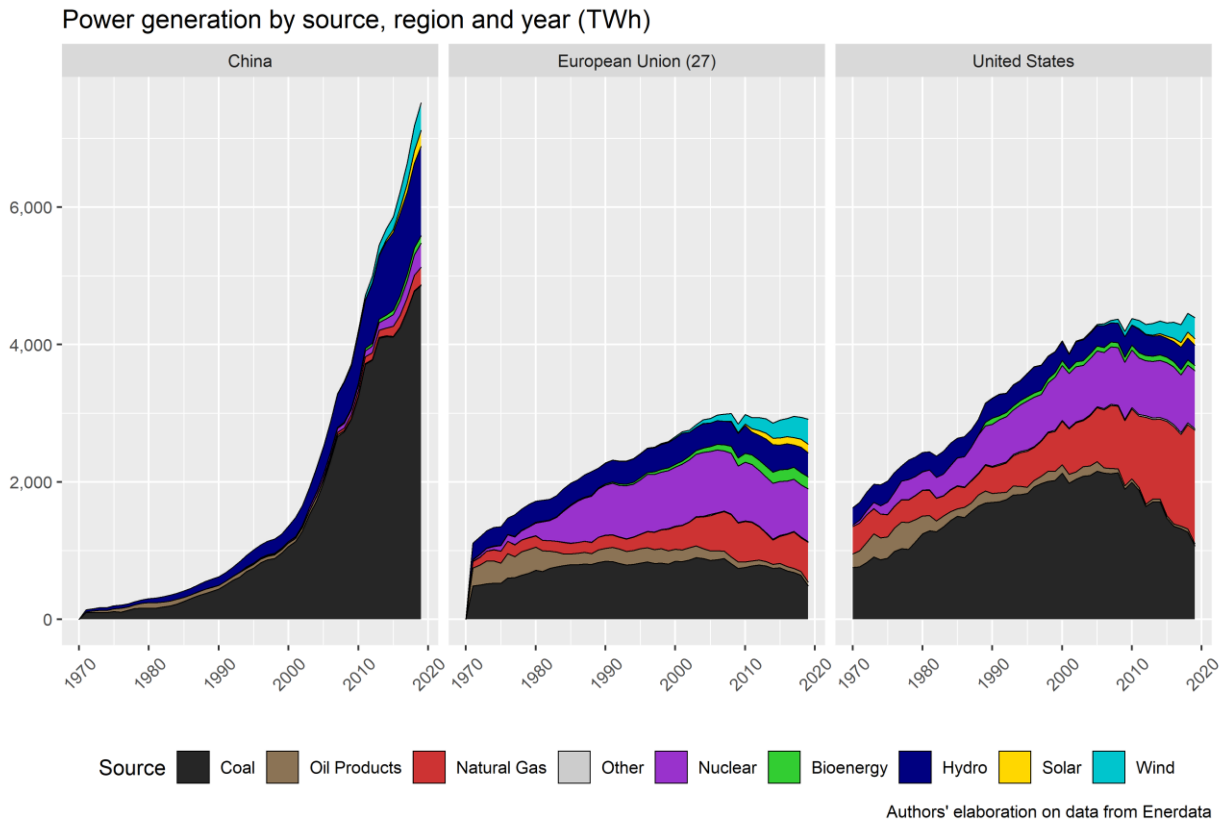

Figure 2 – Electricity generation by region, source and year, 1971-2019, TWh (Authors' elaboration on data from Enerdata).

Finally, the single indicator that is often considered to assess the decarbonization of the power sector is the CO_2 intensity of the electricity, which quantifies the emissions associated to the generation of one unit of electricity (usually expressed in kWh). The evolution of this indicator for the three regions is reported in Figure 3. The chart illustrates a declining trend for all the regions, while differences remain about the absolute level of the CO_2 intensity. The most recent data, for 2019, show that average electricity generation in China leads to the emission of 552 g of CO_2 per kWh, while the same figure is 376 g/kWh for the US and 242 g/kWh for the EU-27. All the regions show a comparable decrease of this indicator over the last three decades: emissions intensity decreased by 45% in the EU-27, 40% in China and 36% in the US. These decreases are mostly related to the evolution of the electricity mix, although a minor contribution is also produced by the improvement of the average conversion efficiency of thermoelectric power plants.

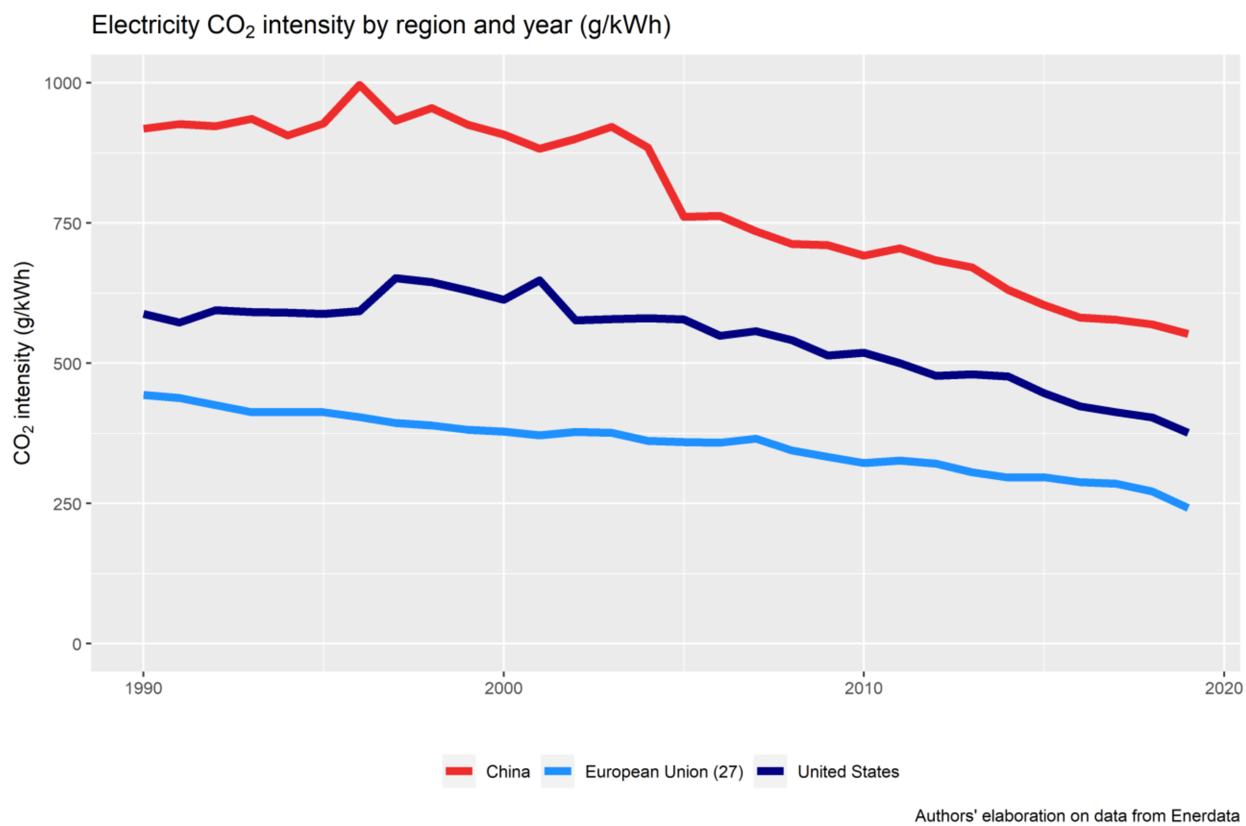

Figure 3 – Electricity CO_2 intensity by region, g/kWh (Authors' elaboration on data from Enerdata).

A final point to be discussed is the autonomy of these three blocs regarding power generation. In some cases, the phase-out of fossil-powered generation leads to an increase of electricity imports. Although net-zero goals are usually focused on local generation, it is clear that a high level of electricity import may become a problem, especially when coming from other regions with higher electricity carbon intensity. The comparison of power supply and demand in these three blocs, which is reported in Figure 4, shows that electricity imports (and in some cases exports) remained limited over the last half century. While China showed a slight surplus generation in the last decades, both the US and the EU-27 are relying on external countries for a small amount of their electricity consumption (generally below 1.5%). For the two importing blocs, the EU and the US, these imports constitute neither an issue of security of supply nor a problem of importing carbon intensive electricity (the US imports mainly from Canada, the EU mainly from Norway and Switzerland).

Additional perspectives can be discussed by considering the power generation at medium-level administrative units, which are presented for the three economies in the following sections.

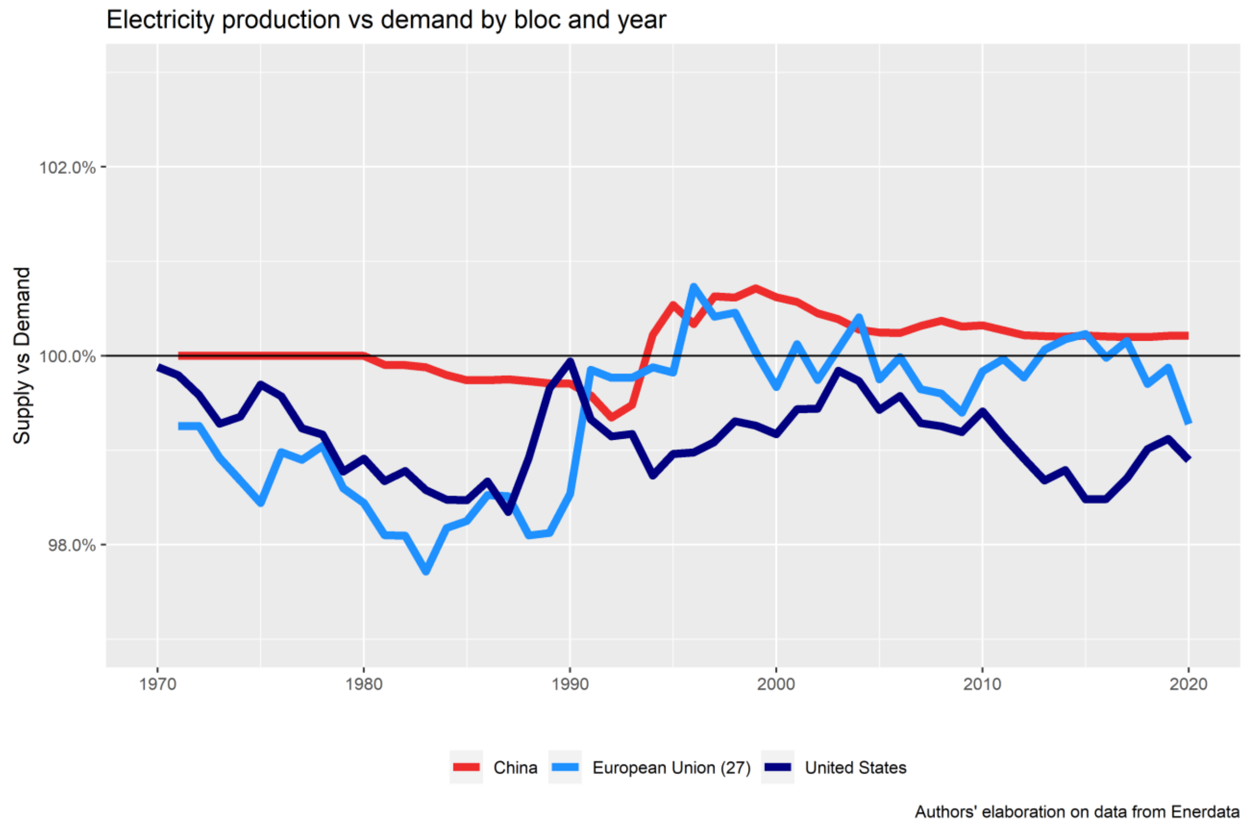

Figure 4 – Electricity supply vs demand by bloc (Authors' elaboration on data from Enerdata).

3.3. Focus on China

Detailed data on power generation at the province level is available from the different editions of the "China Energy Statistic Yearbook", although some information is available only in Chinese.

The evolution of the electricity generation mix is reported in Figure 5 for all the Chinese provinces, while the absolute figures are available in the Appendix (see Figure 14 and Table 2). The chart clearly depicts a large majority of territories relying heavily on thermal power generation, which is in turn mostly relying on coal. The share of natural gas, although increasing in the very last years, still remains marginal. Since no complete data was available at the province level, we preferred to consider the thermal category, for a better representation of the published data. Figure 23 in the Appendix shows the administrative divisions of the People's Republic of China in its 31 provinces.

It is interesting to remark that five provinces (Shandong, Jiangsu, Inner Mongolia, Guandong and Sichuan) out of 31 represent one third of China's power generation, that first nine provinces represent more than half of China's power generation, while and the first 15 provinces reach together three quarters of the total generation (see Table 2 and Figure 20).Some territories show an important share of hydropower, which is in fact dominant in four provinces (Sichuan Province, Yunnan Province, Tibet Autonomous Region and Qinghai Province), and it has a relevant importance in other provinces as well (notably in Hubei Province, Hunan Province, Guangxi Zhuang Autonomous Region, Guizhou Province). Although the share of hydro generation often shows constant trends, it is important to remember that these figures are associated with an increase in its total output, as the total power generation in the country has been showing a continuous and significant increase over the last decades.

The second low-carbon source in the country, nuclear power, is limited to few provinces, since power plants in China are mostly distributed on coastal areas to exploit the availability of seawater for cooling. However, there are many reactors under construction, also in locations that are far from the sealine. Historical generation from nuclear has been limited to Guangdong, Zhejiang and Jiangsu Provinces, although in recent years new reactors came online in Liaoning Province, Fujian Province, Guangxi Zhuang Autonomous Region and Hainan Province. The present reactors are located in the east of the country, and also future reactors are likely to be installed to the east of the Heihe–Tengchong Line[11], to the general lack of cooling water in the western part of the country. Lastly, after Fukushima, new nuclear power projects need to face potential issues related to public opinion and an increased attention to safety risks. Nuclear power may benefit from new technologies, such as some Generation IV nuclear units that are currently in development.

In the very last year China has also pushed on wind and solar power, and although these two technologies remain marginal, their share is rising exponentially. However, subsidies for solar and wind energy are currently being phased out, and the future development of solar and wind energy will be more market driven. Wind generation is gaining momentum in several regions[12], although the strong increase of installed power has sometimes overpassed the available transport capacity of high-voltage transmission lines, leading to issues of wind output curtailment. This is mostly due to the distance between wind power generation locations, mostly in the North and North-West, and sites of electricity consumption. Another reason of wind and solar curtailment is also institutional barriers of cross-provincial power transmission. For example, resistance comes from grid companies because of their revenue model embedded in the Chinese power market design.

[11] This ideal diagonal line, stretching from the city of Heihe in northeast to Tengchong in south, is dividing the country in two areas of around the same surface, but more than 90% of the Chinese population lives east of the line.

[12] These regions are: Gansu Province, Inner Mongolia Autonomous Region, Heilongjiang Province, Ningxia Hui Autonomous Region, Xinjiang Uygur Autonomous Region, Jilin Province and Hebei Province.

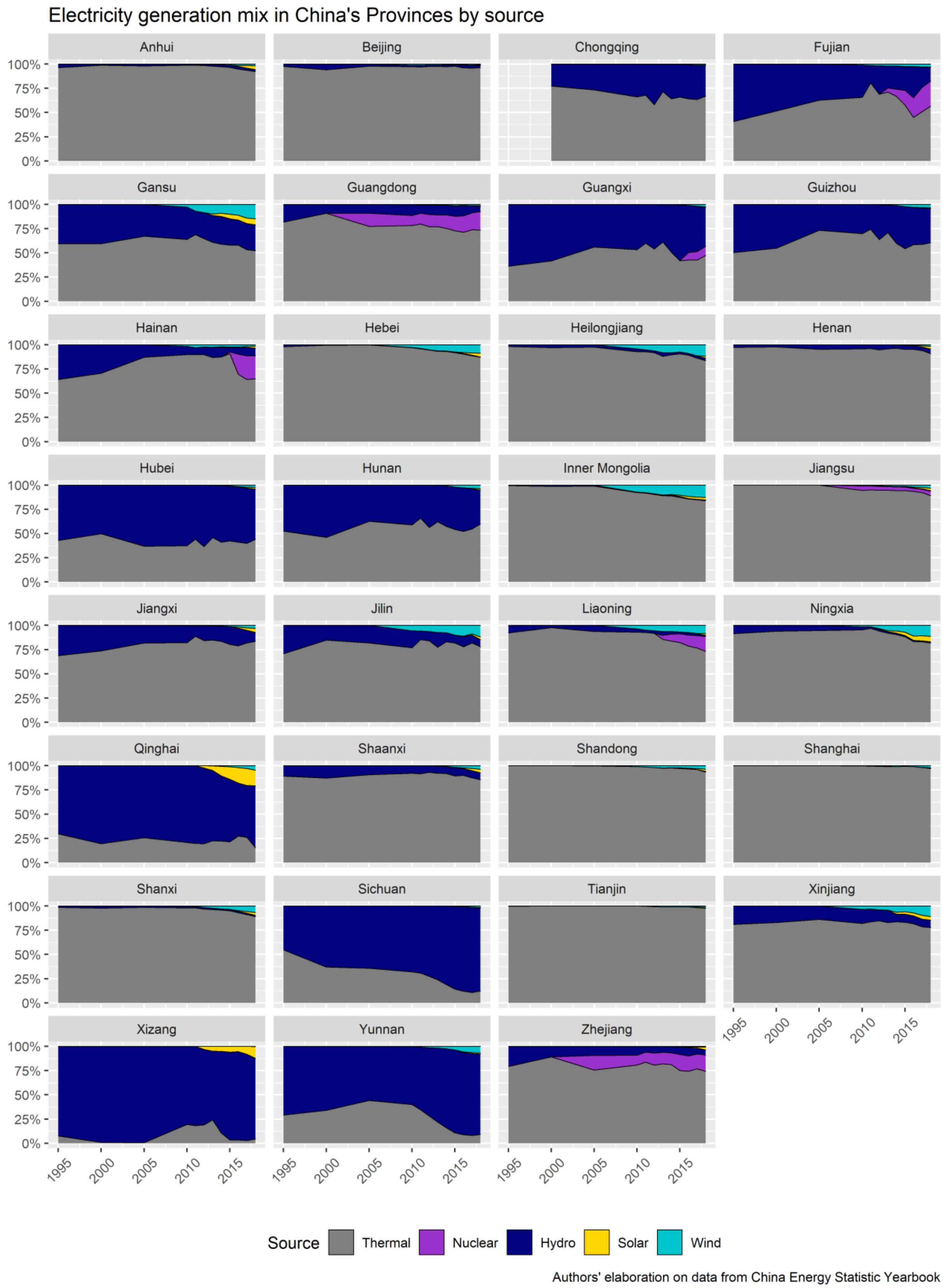

Figure 5 – Electricity generation mix in Chinese provinces by year, 1995-2018 (Authors' elaboration on data from China Energy Statistic Yearbook).

In parallel, also solar generation is increasing, as China remains the first country worldwide for solar generation (with more than 250 GW of installed capacity as of 2020[13], around one third of the global installed capacity), in addition to its strong leadership in solar panels manufacturing. The provinces that saw the highest share of solar generation in their electricity mix in the last years are Qinghai Province, Tibetan Autonomous Region, Ningxia Hui Autonomous Region and Gansu Province. Wind and solar curtailment has been identified as a key problem. To cut down the curtailment rate, the government has put forward policies such as guaranteed consumption of renewable energy sources as well as Green Electricity Certificate (GEC).

Figure 6 shows the evolution of the CO_2 electricity intensity that has been calculated for selected Chinese provinces. In the absence of more detailed data, our estimation is based on the national emission factor of thermal power generation applied to each province. Thus, the result on the plot is based on the share of thermal power generation in each territory.

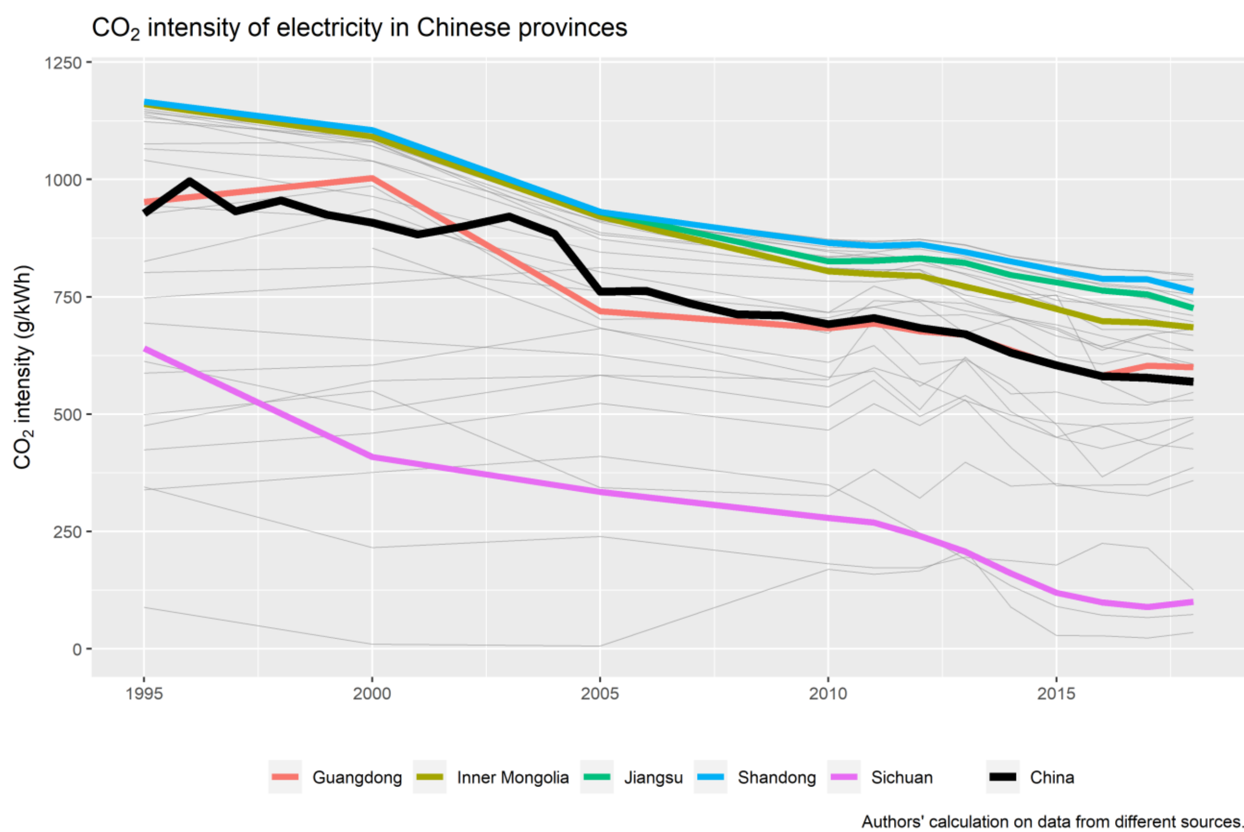

Figure 6 – Electricity generation CO_2 intensity in Chinese provinces, g/kWh (Authors' calculation on data from different sources).

[13] Source: IRENA, Country rankings.

Although this approach leads to an approximation of this indicator, due to the different contribution of natural gas in thermal generation across provinces, such contribution remains marginal in comparison with the very high share of coal in Chinese power plants (see Figure 1).

The figures show an important variability across provinces, although most of the ones with the largest power generation (which are highlighted in colour in the chart) have high shares of thermal power generation. A decreasing trend is noticeable in all the provinces, reflecting the national trend, although with some occasional increases, especially at the beginning of the 2010s. The strong decrease in Sichuan, the fifth province for total power generation, is caused by the rising share of hydropower in its electricity mix, reaching almost 90% in 2018.

A comparison of power generation and consumption in Chinese provinces shows significant imbalances, due to the disparity between availability of resources and significant power demand, mainly related to large urban areas and industrial sites. Figure 7 shows the historical evolution of supply and demand across provinces, with the coloured lines referring to the five areas with higher electricity generation.

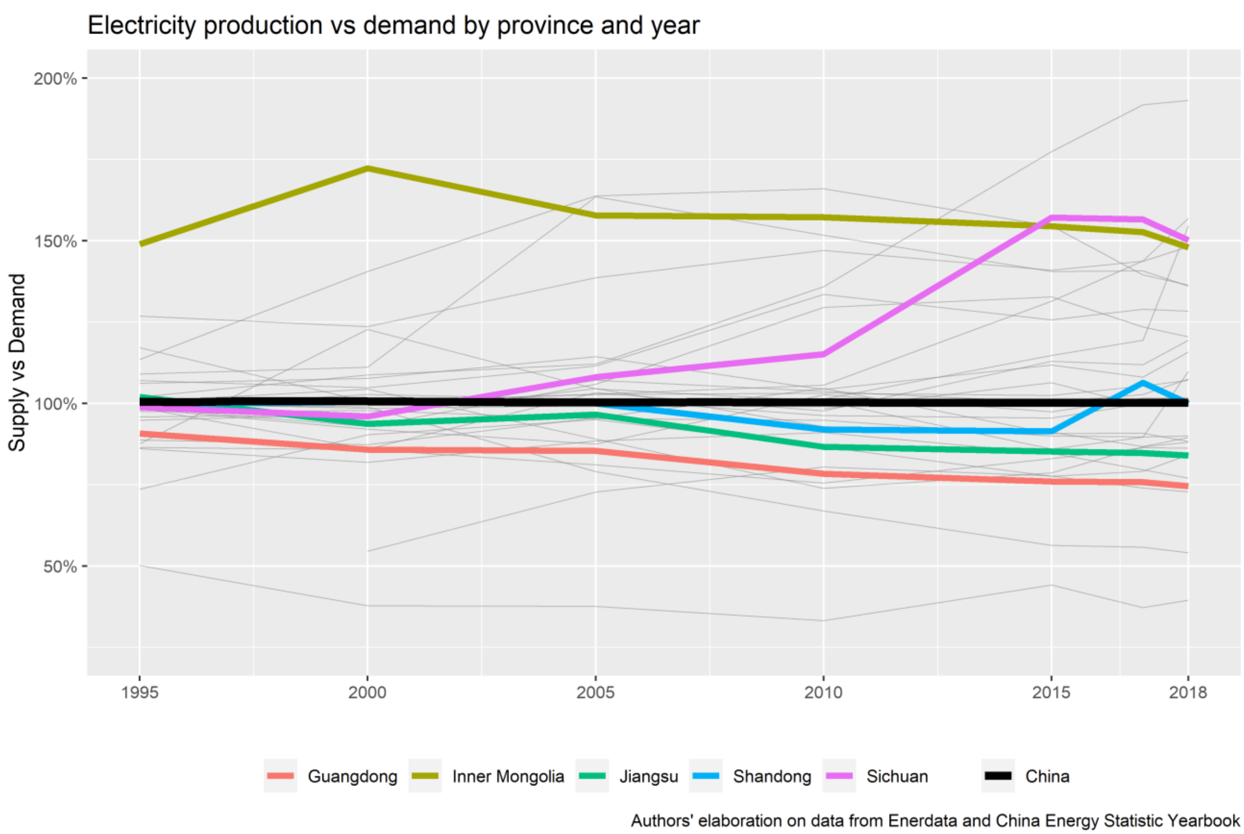

Figure 7 – Electricity supply vs demand in Chinese provinces (Authors' calculation on data from Enerdata and China Energy Statistic Yearbook).

While the main provinces on the eastern coast are generally showing a certain level of import, both Sichuan Province and Inner Mongolia Autonomous Region are characterized by a significant overgeneration. Similar imbalances are likely to remain in a decarbonized power system, due to the variable potential of renewables across regions. For this reason, massive investments in transmission grids are expected, and in some cases already planned, to connect production areas with consumption sites and avoid curtailments caused by bottlenecks in transmission capacity. Power market reform is also under way, including measures to reform the renewable power tariff, development of the auxiliary service market and reform of the grid companies' revenue model.

We have included a map of the Chinese provinces, reported in Figure 17 in the Appendix, illustrating the first source of power generation per each region, together with its share. The figure shows that the largest part of provinces remains powered primarily by thermal energy (with variable shares), although in some mountain regions hydropower represents the lion's share.

3.4. Focus on the European Union

The EU-27 is characterized by very different countries (Figure 24 shows a map with all Member States constituting the European Union (EU-27)), on the many dimensions that have an impact on the electricity mix, including the size, the distribution of final sectors, the availability of primary energy sources, the historical development of infrastructures and final sectors, etc.

A general representation of such a variability is reported in Figure 8, which depicts the historical evolution of the electricity mixes in EU countries. A parallel chart with the absolute values is reported in the Appendix of this paper (see Figure 15, Figure 21 and Table 3 with relevant data). The first six countries out of 27 represent 72% of EU power generation, and Germany, France and Italy alone reach half of the total power generation in the bloc (with 47% of its population). On the other hand, the 15 countries with the lower power generation sum up to only 11% of the entire bloc. The charts clearly demonstrate the variable conditions that affect EU countries. In some cases, coal remains a dominant or important source, including for Poland, Czech Republic, Bulgaria, Germany and Slovenia, although it almost always shows a decreasing trend over the last three decades. In other countries this role has been played by nuclear, such as in France, Slovakia, Hungary and Belgium. Lithuania was also heavily reliant on nuclear power, which represented 70-80% of its demand up to 2009, when Ignalina, the country's only nuclear power plant, has been closed. This has led to a huge variation of the national electricity mix and shifting the country from an electricity net-exporter to a net-importer.

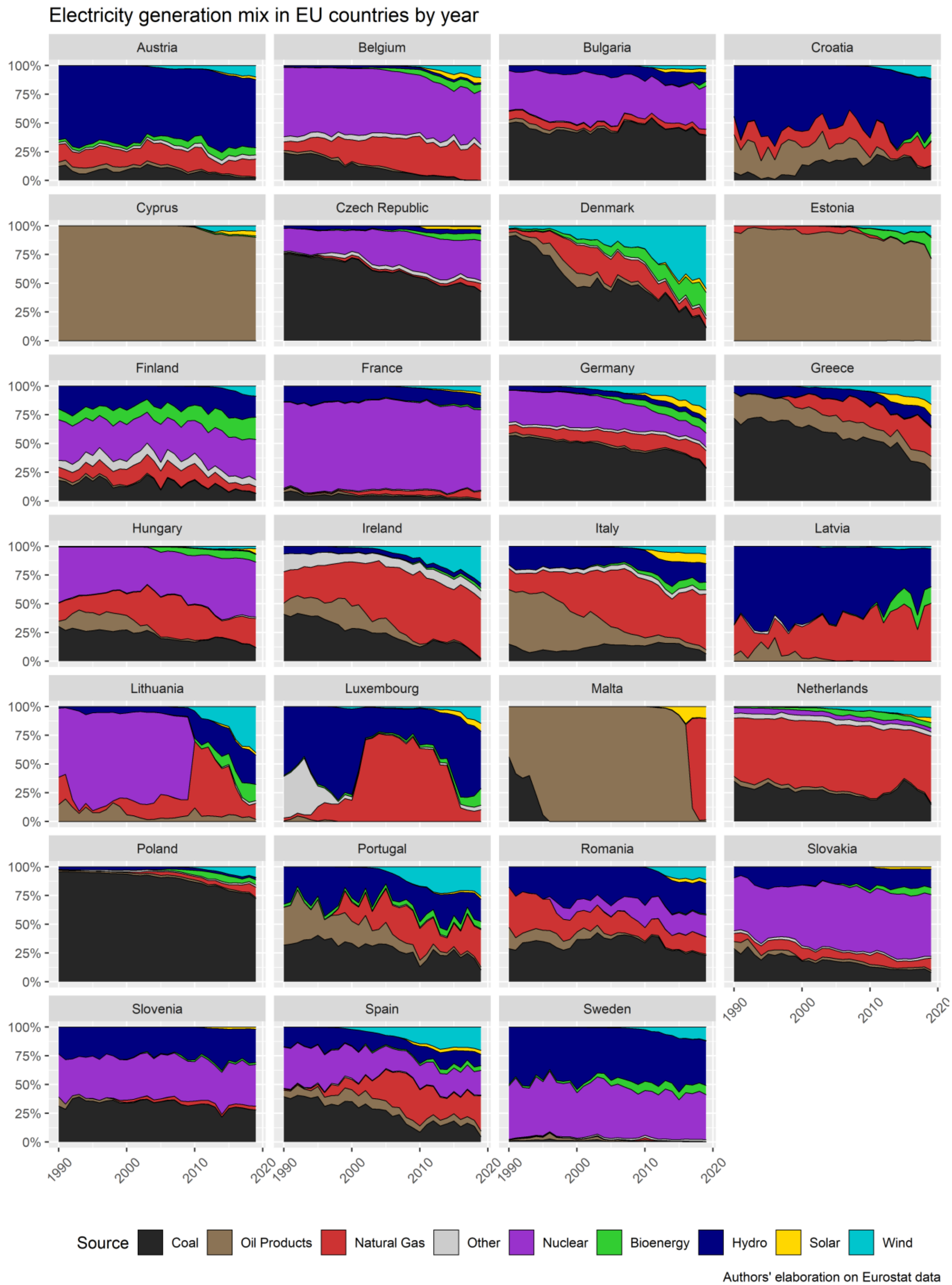

Figure 8 – Electricity generation mix in EU countries by year, 1990-2019 (Authors' elaboration on Eurostat data).

Other countries are currently relying for about half of their power generation on natural gas, such as the Netherlands, Ireland, Latvia and Italy. Finally, Cyprus and Malta strongly rely on oil products (and the latter on natural gas lately), although since April 2015 the Malta-Sicily electricity interconnector has improved the energy security of the island. As we will discuss later, electricity imports and exports are playing an important role in Europe, especially for small countries. Finally, considering fossil sources, the case of Estonia is worth mentioning, since 70% of its power generation is based on shale oil, due to the high availability of this resource in the country.

Considering renewable energy sources, hydro power plays a crucial role in many countries, and mostly in Austria, Croatia and Sweden (and additionally in non-EU countries such as Switzerland and Norway). Wind energy has increased significantly in the last decade in many countries, and especially in Denmark where it is now responsible for 55% of the national power generation. Other countries that are showing interesting trends for wind power are Lithuania, Ireland, Portugal, Germany and Spain. Bioenergy reaches 15-20% of the total in Denmark, Finland and Estonia, while solar energy represents 5-10% of total generation in Italy, Germany and Greece (and a slightly lower share in Malta and Luxembourg).

Although the variability is significant, a general trend towards low-carbon power generation is noticeable, which is the result of the EU's strong targets that have been set over the last decades and will continue to characterize the future energy system. Wind and solar appear to be the most promising solutions to foster this transition, although their availability depends on geographic features of each country. The Mediterranean countries are generally benefitting from higher irradiation rates, while in Northern Europe the availability of wind is generally higher, especially in offshore sites. However, both these sources will likely need a proper deployment of flexibility solutions to cope with their variable nature, if they are to represent a dominant share of the total power generation at the country level.

The result of the aspects mentioned above is a generalized decreasing trend of CO_2 intensity for the electricity generated in EU countries, although very variable from one country to another (see Figure 9). The six countries with the highest total power generation in absolute terms have been highlighted in colour in the chart. While the highest values for Poland are related to the significant share of coal plants, the lowest levels in the chart are the result of a dominant share of nuclear and hydro in Sweden and nuclear in France.

An additional aspect to be considered is the imbalance between power generation and consumption in EU countries. Figure 10 reports its historical variation, showing a significant variability across regions, and, to a minor extent, across time. Countries like France and Sweden have an historical over-generation, partly related to the significant share of nuclear power in their electricity mixes, while other countries, such as Italy, are relying on electricity imports to cover part of their demand. These choices are generally related to economic reasons, and the oscillations over time are also due to the variability of the energy consumption and the power generation plants. Still, this aspect will be crucial when addressing the distribution of decarbonization goals across EU countries.

The various energy mixes of EU countries are also clear when considering the first electricity source per each country, as reported in Figure 18 in Appendix. We see that in the majority of cases coal, natural gas and nuclear power represent the first source, although with variable shares. In few small countries, hydropower (Austria, Croatia and Luxembourg), wind energy (in Denmark and Lithuania) and oil products (Estonia and Cyprus) emerge as the first solution for electricity production.

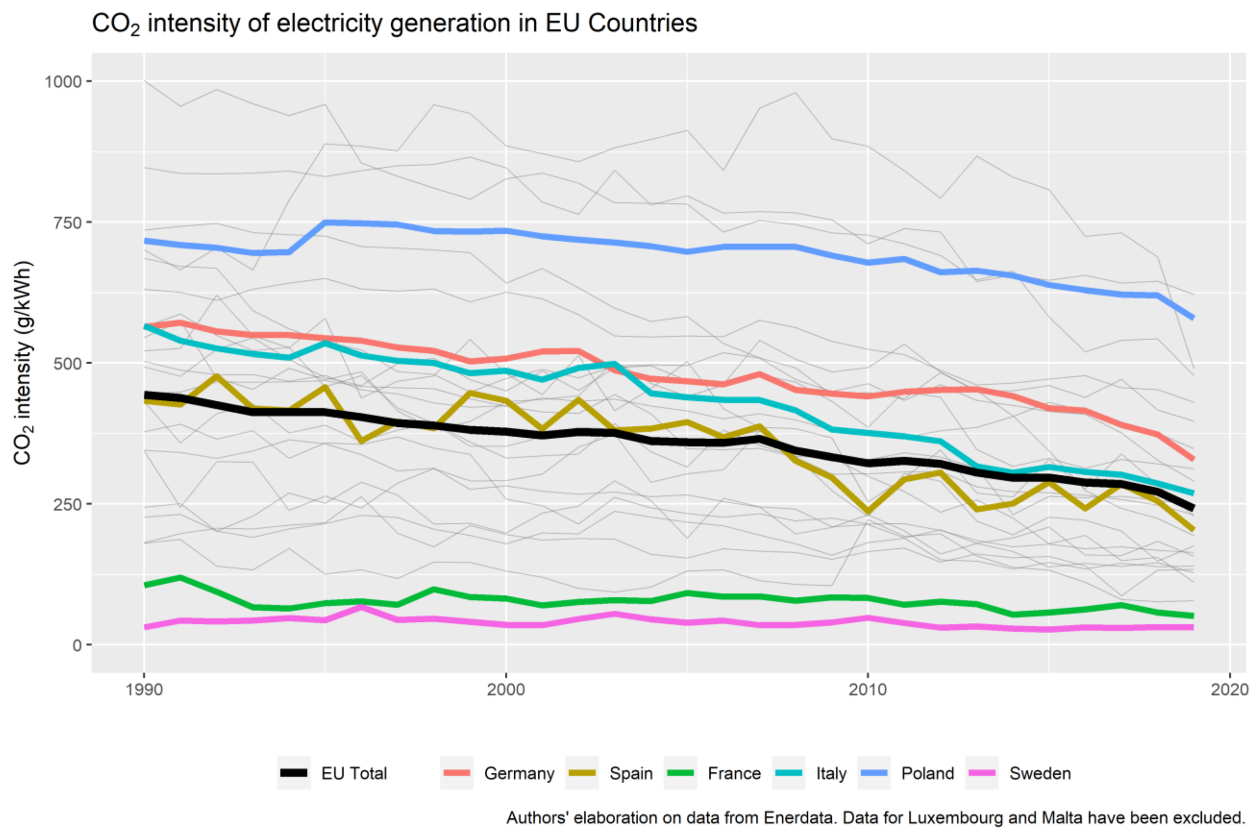

Figure 9 – Electricity generation CO_2 intensity in EU countries, g/kWh (Authors' elaboration on data from Enerdata).

As discussed above, the future efforts to reach a decarbonized power sector in the EU-27 will not be equally distributed across countries. For this reason, it is important to account for these differences, also considering the available and planned network infrastructure, both at country level and for the interconnection across national electricity markets. Moreover, it is important to remark that the construction of new transmission lines across the EU may be difficult, both from a public opinion point of view (unless they are buried, which renders them very expensive) and from a governance point of view (who is to pay for the infrastructure). Reaching such a challenging goal will necessarily require an optimal cooperation across countries, and the policy and regulatory measures that need to support such a transition will also need to address the likely evolution of cross-border electricity flows. That's why the future scenarios being considered at a continental level need to be developed with a strong cooperation across countries.

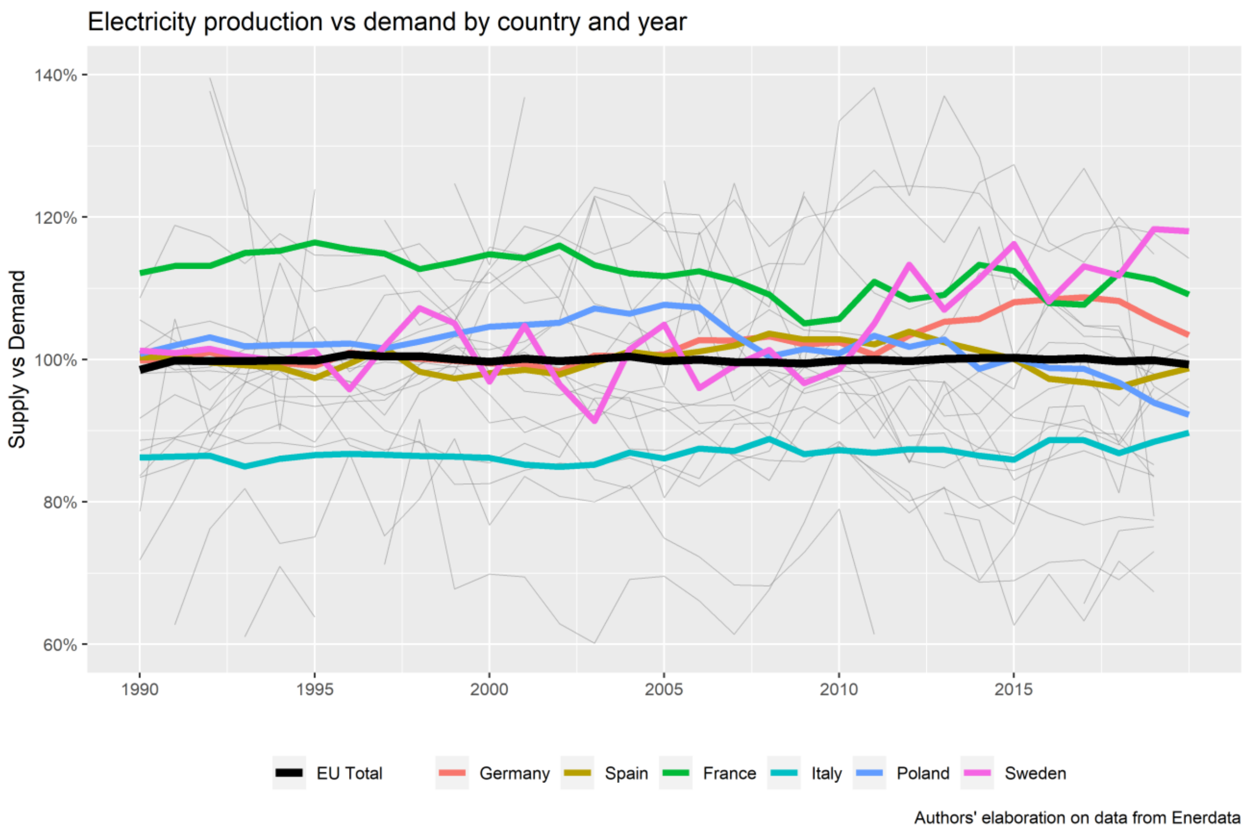

Figure 10 – Electricity supply vs demand in EU countries (Authors' elaboration on data from Enerdata).

3.5. Focus on the United States

As discussed in the previous sections, these large economic blocs are the result of many medium-level administrative units with many differences, and the US is no exception. The historical evolution of power generation across states has led nowadays to a picture composed by wide ranges in terms of electricity mix, generation potential, electricity prices, under- and over-supply.

Figure 11 reflects the variability of medium-level administrative units that we have already discussed for the EU and, to a minor extent, for China. Additional information is available in the Appendix section (see Table 4 and Figure 16 and 22). Five States (Texas, Florida, Pennsylvania and Illinois) out of 50 represent one third of US power generation, the largest eleven states represent more than half of US power generation, while half of the States sum up to 80% of the total generation in the country. Figure 25 shows a map with the 50 States which represent the United Stated of America.

In the US, the largest state for electricity generation is Texas: with 483 TWh of total generation in 2019, it outperformed the combined generation of Florida (246 TWh) and Pennsylvania (229 TWh), which rank 2nd and 3rd. It is interesting to remark that electricity production is not always in line with the population: California, with 40 million inhabitants, has a lower generation than Pennsylvania (13 million). While the former has a significant share of electricity imports, the latter shows an excess of production that is exported to neighbouring states. A fundamental point is that Texas is also the only state in the continental US with its own electricity grid, which is disconnected from the neighbouring states. This aspect has played a crucial role in the massive power outages caused by a severe winter storm of February 2021: given the lack of enough available supply capacity, Texans could not be supported by spare capacity in other states. The other states are interconnected in two major power grids, which allow them to increase their resilience, the Western Interconnect and the Eastern Interconnect (although the general transmission capacity in the US is greatly underdeveloped and missing billions of needed investment). Instead, Texas historically remained a separate grid to avoid the need of complying with federal laws and regulations on electricity tariffs and services, and in part for the cultural idea of the independence of Texas. The first source of electricity generation in Texas is currently natural gas (53%), followed by coal (19%), wind (17%) and nuclear (9%). The other three large consumers are Florida, Pennsylvania and California. Just like in Texas, in all these states the first source is natural gas, representing 74%, 43% and 42% of power generation in 2019 respectively. In Pennsylvania the largest share of the remainder is matched by nuclear power, reaching 36% of the generation, while California shows a very diverse mix (mostly with hydro, solar, nuclear and wind). These four states represent almost 30% of the total power generation in the US. The other states show various electricity mixes, although a clear shifting trend from coal to natural gas has been noticeable (in particular in Alabama, Delaware, Georgia, Mississippi, Nevada and Virginia) over the last decade thanks mainly to the strong development of shale gas production.

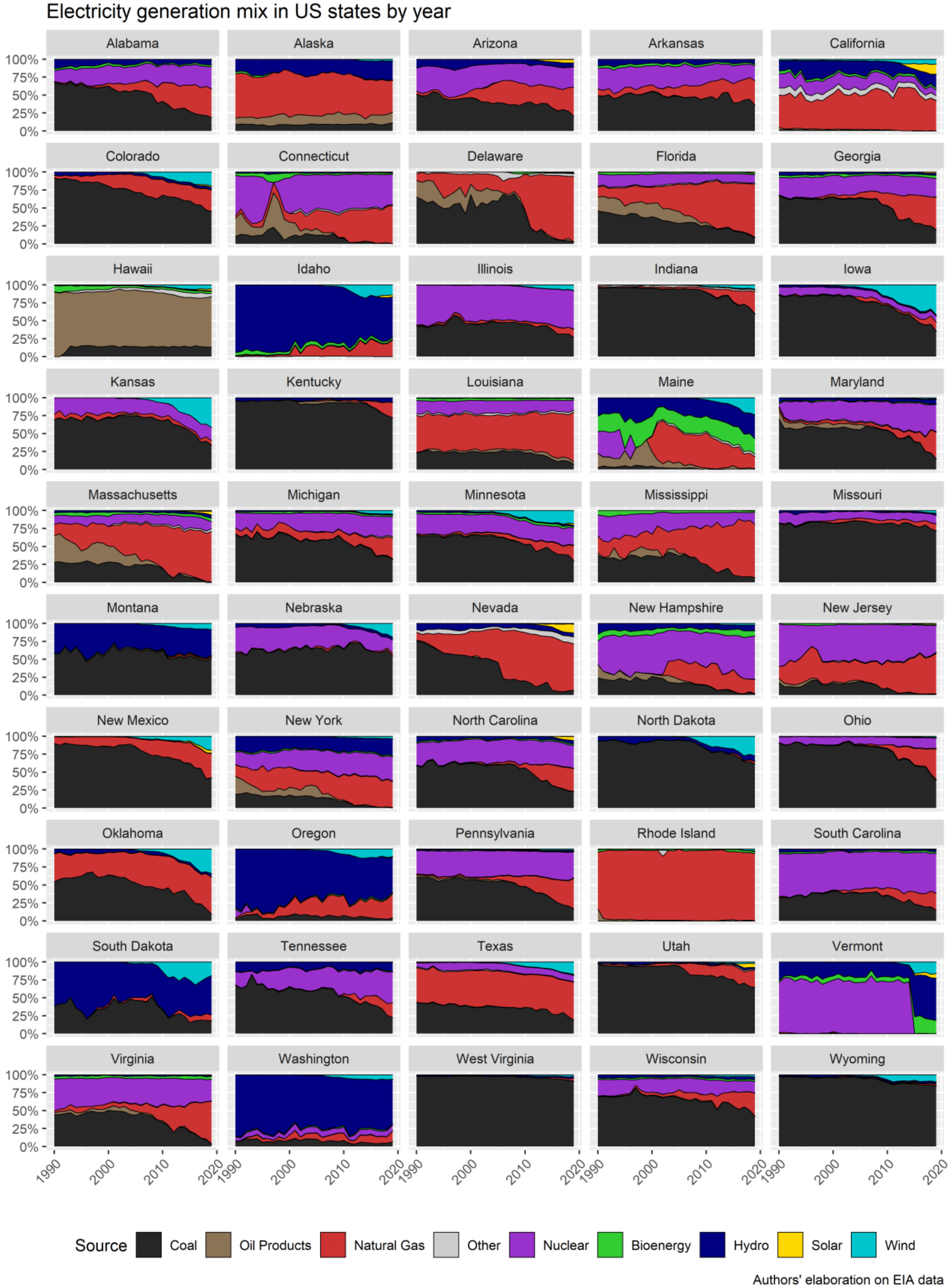

Figure 11 – Electricity generation mix in US states by year, 1990-2019 (Authors' elaboration on EIA data).

Considering renewables, some states have historically relied on hydropower as the main source for electricity generation (in Idaho, Oregon, South Dakota, Washington and recently in Vermont), while in others wind is showing an important increase during the last 5 years (mostly in Iowa, Kansas, Maine, North Dakota and Oklahoma). Solar energy represents a noticeable share in 2019 only in California (14%) and Nevada (12%), and bioenergy in Maine (21%) and Vermont (19%). Finally, nuclear power remains an important source in almost half of the states, being the first source in Illinois, New Hampshire and South Carolina (and in Vermont before the shutdown of the Entergy Nuclear Vermont Yankee power station in December 2014). After the Three Mile Island accident in 1979, no new power plant has been built in the US, until two plants started the construction phase in 2013 in Georgia. Still, the future of nuclear in the US remains unclear. While some existing plants have faced early retirements due to legal and social pressures, some companies are investing in new technologies, such as small-size nuclear reactors. Despite the little public sentiment in support of new nuclear plants, this source will likely remain crucial to reach the zero-carbon targets ahead.

As a result of these various electricity mixes, also the CO_2 intensity of American states show a considerable variability. Figure 12 highlights its wide range over the years, with a clear decreasing tendency in the last years, especially in some large states (the five states with the highest power generation are reported in colour in the chart).

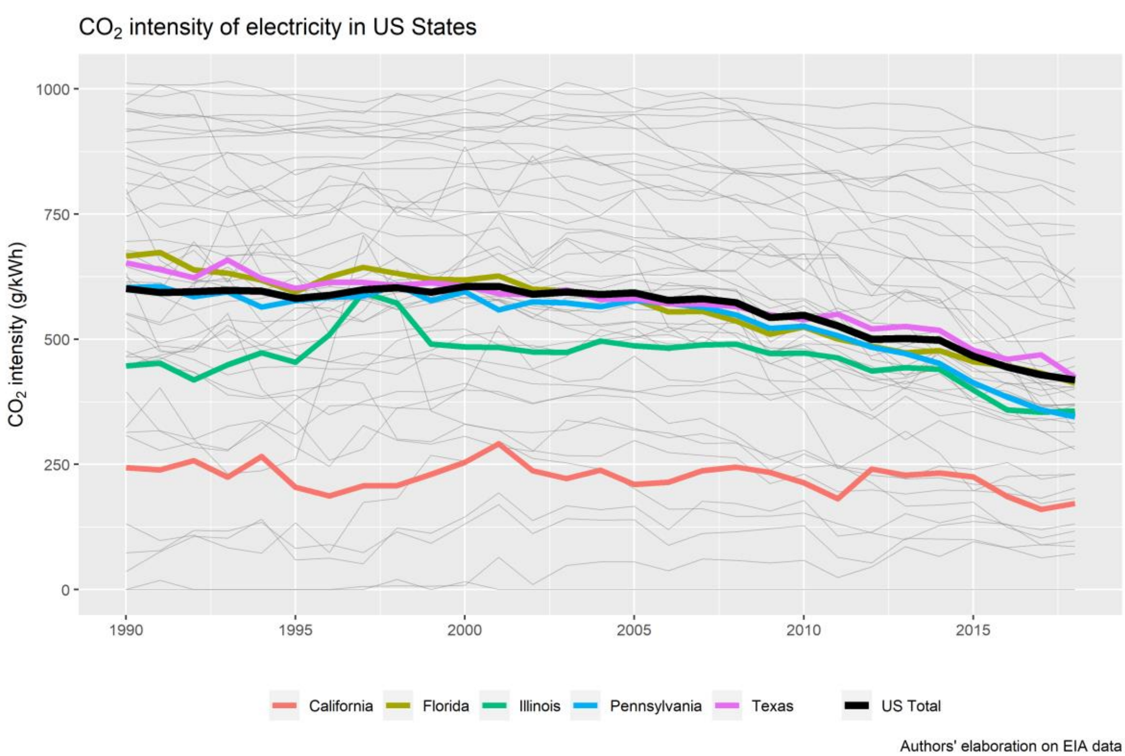

Figure 12 – Electricity generation CO_2 intensity in US states, g/kWh (Authors' elaboration on EIA data).

This tendency is both related to the increasing role of renewables as well as to the transition from coal to natural gas. However, it is important to remark that in many states the CO_2 intensity remains well above 475 g/kWh, which is the global average for 2018 [19].

As discussed above for both China and the EU, also in the US there is an important imbalance between generation and consumption across medium-level administrative units. Figure 13 shows the historical evolution of the ratio between supply and demand, comparing this figure at the state level with the value for the US (which is reported in black, and shows a very narrow imbalance, as already discussed before). Some states are not reported in the chart, or partially reported, since in some years their oversupply exceeded 200% (for North Dakota, West Virginia and Wyoming).

Just like in the other blocs described in this paper, these data clearly show that also the US are represented by many different administrative units. This variability also clearly emerges when considering the first electricity source in each state (as reported in Figure 19 in Appendix). Dedicated strategies and policies are of utmost importance, to properly leverage on the potential of each geography, but also the importance of interstate transmission grids emerges from the historical figures that are analysed.

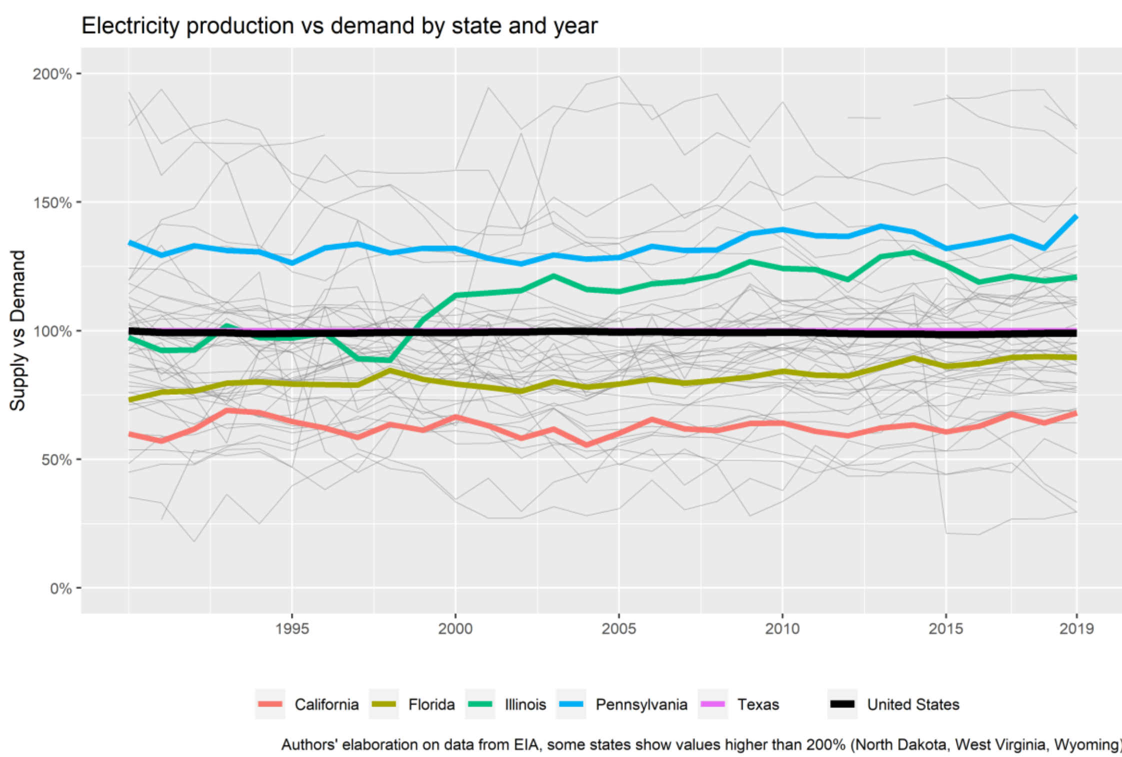

Figure 13 – Electricity supply vs demand in US states (Authors' elaboration on EIA data).

4. Discussion and conclusions

The figures presented in the previous sections highlight the wide variability of electricity mixes that contribute to the high-level administrative units that are often responsible for climate targets and policies, and that have committed to become carbon neutral by 2050 or 2060. Such figures depict the complexity of the electricity generation mixes, and their evolution over time for each region is the result of multiple factors related to the economic, (geo)political, environmental and social dimensions. The strategies and pathways towards carbon-neutral energy and economic systems require to carefully address this complexity, by leveraging on the specific opportunities offered by each territory. A successful dialogue between different administrative levels will also be crucial to reach an effective deployment of the required measures.

A consistent shift from fossil-based power generation towards low-carbon alternatives is urgently needed, and many regions already show that it is possible to operate grids with high shares of renewable energy, although often thanks to an adequate interconnection with neighbouring regions. In addition to renewable sources, which are expected to represent the lion's share of a future 100% clean energy generation, the role of nuclear power as well as carbon capture technologies will need to be clearly addressed. In many regions, it is unlikely that renewables alone will be able to supply the massive amount of low-carbon electricity that will be needed to reach these challenging targets.

This paper has been mostly focused on figures depicting the supply-side, but the matching of future electricity consumption patterns will also require additional flexibility solutions, to compensate for daily or seasonal mismatches, especially in power systems with a high share of non-dispatchable renewables. Such solutions may include electricity storage under different forms, sector coupling, demand-side management and interconnections. The role of electricity interconnections will be of particular importance in geographies with a spatial mismatch between areas with high renewable potential and urbanized and industrialized areas but also to cope with the variability of non dispatchable renewable power sources. All these different flexibility options need to be developed in parallel, since they all provide complementary benefits and opportunities, and no single solution will be enough to match the increase in demand flexibility.

In addition to the historical trends, a further increase of electricity demand can be driven by an expected important electrification of final uses. This phenomenon has already been in place in the past, but the electrification rate is anticipated to increase much more in the future if the final sectors are due to reach net-zero emissions. This increase could be in some cases partly compensated by an increase in efficiency in specific applications, thanks to technological improvements (such as electric vehicles, heat pumps, innovative industrial applications).

We conclude our work by highlighting some policy recommendations that we believe can help the decarbonization of the power sector in these economies:

- There is a need of specific and credible targets for the power sector, which are based on the expected increase of demand, together with its spatial dimension, and the actual renewable potential (and flexibility needs) across the regions.
- In addition to the final goal, it is important to build clear milestones and pathways based on the current condition of different regions, together with intermediate targets and a clear and transparent monitoring process, the results of which should be used to adjust the pathway over the years. Many research works highlight the fundamental impact of different pathways towards net zero on the cumulative emissions.
- It is also important to focus on the electricity consumption and not only on the generation, by accounting also for possible electricity imports and exports from and to other regions. The shift towards a consumption-based accounting of CO_2 may also help to increase the responsibility of the final consumers.
- Other environmental impacts need also to be taken into account, including local pollution, toxicity and impact on biodiversity, to avoid that the urgency of the climate change will lead to negative effects on the environment and the human health.
- Governments should increase the use of participatory processes, by improving the communication of these goals and their importance, and by applying dedicated policies to compensate energy poverty issues that may increase due to a costly phase-out of fossil fuels. The concept of the “just transition” defined by the EU should be guaranteed, in parallel with the development of a clean power system.
- More emphasis is needed on the horizontal coordination and network, instead of only focusing on vertical management. This means the coordination process among provinces/states/EU countries on the cross-border electricity transmission, with the aim of matching of the supply and demand. This also means cross-learning opportunities among provinces/states/EU countries. Lastly, dialogues need to be held with private sector players along the power value chain – independent power generation companies, local big industrial companies as power consumers, regional grid companies etc. Economic incentives need to be aligned with command-and-control measures.

This work presents some historical statistics with the aim of illustrating the complexity of different blocs around the world, with a specific focus on the differences that lay behind country-level (or

EU-level) figures. Still, this data is not able to fully represent additional aspects, such as the temporal variability over the day and the seasons, which is an additional dimension to be considered when planning reliable and secure power networks. Also, the economic and social dimensions of this transition have not been discussed, although they clearly represent a fundamental point of discussion. This paper aims at presenting a first step towards the comparison of different features of these three large economic blocs in their pathways towards a low-carbon future.

References

[1] International Energy Agency. Share of electricity in total final energy consumption, historical and SDS – Charts – Data & Statistics 2021. https://www.iea.org/data-and-statistics/charts/share-of-electricity-in-total-final-energy-consumption-historical-and-sds (accessed July 14, 2021).

[2] International Energy Agency. Share of low-carbon sources and coal in world electricity generation, 1971-2021 – Charts – Data & Statistics 2021. https://www.iea.org/data-and-statistics/charts/share-of-low-carbon-sources-and-coal-in-world-electricity-generation-1971-2021 (accessed July 14, 2021).

[3] Froggatt A, Quiggin D. China, EU and US cooperation on climate and energy An ever-changing relationship 2021.

[4] European Commission. 2050 long-term strategy | Climate Action n.d. https://ec.europa.eu/clima/policies/strategies/2050_en (accessed July 29, 2021).

[5] BBC News. Climate change: China aims for "carbon neutrality by 2060" n.d. https://www.bbc.com/news/science-environment-54256826 (accessed July 29, 2021).

[6] White House. FACT SHEET: President Biden Sets 2030 Greenhouse Gas Pollution Reduction Target Aimed at Creating Good-Paying Union Jobs and Securing U.S. Leadership on Clean Energy Technologies | The White House n.d. https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/fact-sheet-president-biden-sets-2030-greenhouse-gas-pollution-reduction-target-aimed-at-creating-good-paying-union-jobs-and-securing-u-s-leadership-on-clean-energy-technologies/ (accessed July 29, 2021).

[7] Merlin C. The Herculean Task of Decarbonizing the American Power System by 2035. Notes de l'IFRI 2021.

[8] Cambridge Econometrics. China's net zero ambition could boost GDP by 5% during this decade 2020.

[9] Braun S. Is China's five-year plan a decarbonization blueprint? Dtsch Welle 2021.

[10] Zhang X, Zhou L. Subnational Climate-Change Policies in China. In: Stavins RN;, Stowe RC, editors. Subnational Clim. Chang. Policy China, Cambridge, Massachusetts: Harvard Project on Climate Agreements; 2020.

[11] Davidson M. Creating Subnational Climate Institutions in China. In: Stavins RN;, Stowe RC, editors. Subnational Clim. Chang. Policy China, Cambridge, Massachusetts: Harvard Project on Climate Agreements; 2020.

[12] Tan X. China's Low-Carbon Policies and Results from a Regional Case Study. In: Stavins RN;, Stowe RC, editors. Subnational Clim. Chang. Policy China, Cambridge, Massachusetts: Harvard Project on Climate Agreements; 2020.

[13] Wong C. More Sticks and Fewer Carrots? Looking Ahead to Implementation of Environmental Policy Under the "New Normal." In: Stavins RN;, Stowe RC, editors. Subnational Clim. Chang. Policy China, Cambridge, Massachusetts: Harvard Project on Climate Agreements; 2020.

[14] International Energy Agency. The Role of China's ETS in Power Sector Decarbonisation. 2021.

[15] Karplus VJ. Coexistence or Obsolescence? The Fate of China's Emissions-Trading Pilots Under a National System. In: Stavins RN;, Stowe RC, editors. Subnational Clim. Chang. Policy China, Cambridge, Massachusetts: Harvard Project on Climate Agreements; 2020.

[16] US Climate Alliance. United States Climate Alliance 2020. https://static1.squarespace.com/static/5a4cfbfe18b27d4da21c9361/t/6102c9aaf637f965fb2bbd75/1627572651414/US+Climate+Alliance+Fact+Sheet_2021.pdf (accessed August 11, 2021).

[17] Stavins RN. Subnational Carbon-Pricing Policy in the United States. In: Stavins RN;, Stowe RC, editors. Subnational Clim. Chang. Policy China, Cambridge, Massachusetts: Harvard Project on Climate Agreements; 2020.

[18] Plumer B. Blue States Roll Out Aggressive Climate Strategies. Red States Keep to the Sidelines. New York Times 2019.

[19] International Energy Agency. Global Energy and CO2 Status Report 2018 2018.

Appendix

This section reports additional figures on the electricity generation and a set of maps of the territories that have been analysed in this paper.

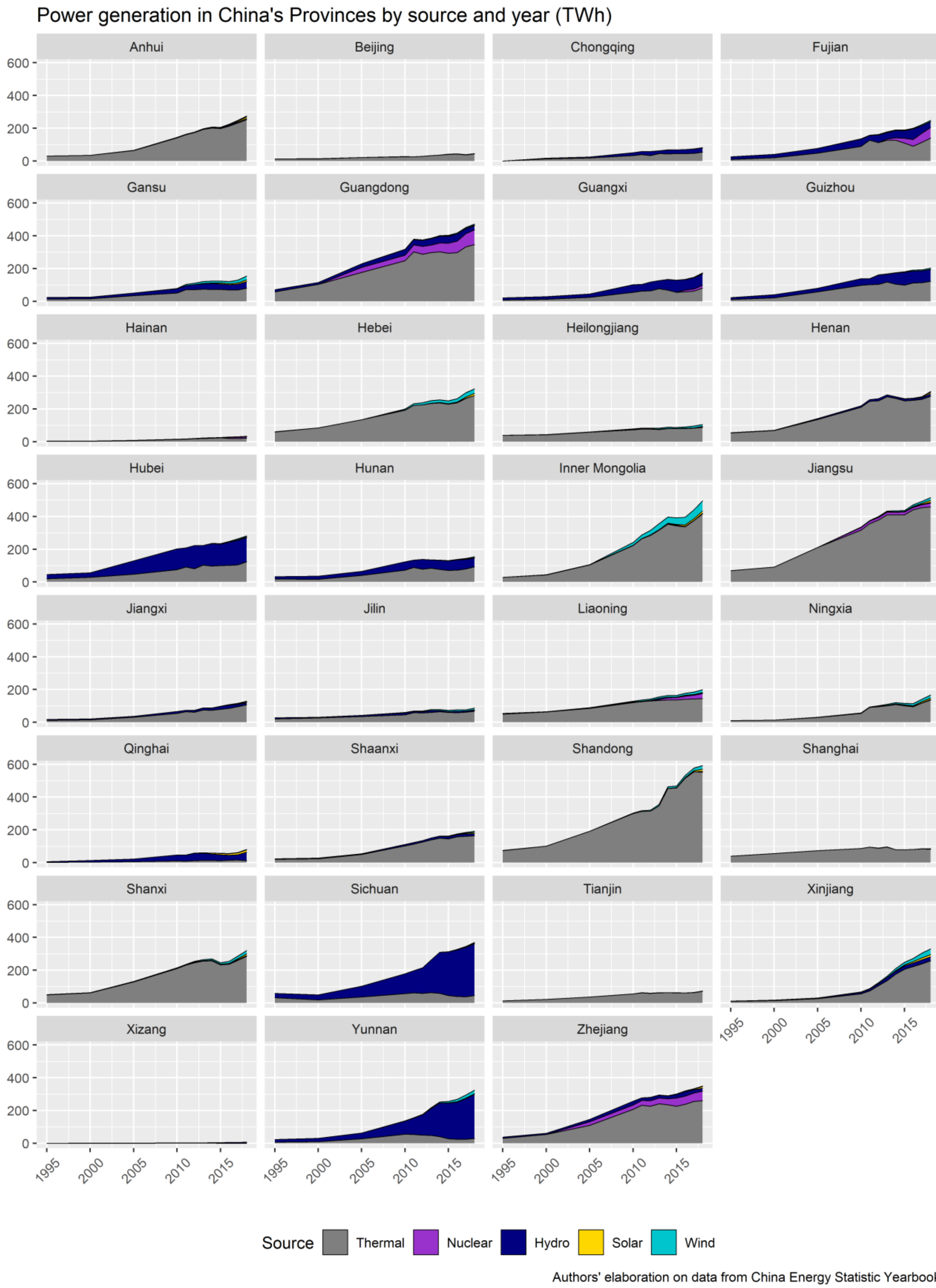

Figure 14 – Electricity generation in Chinese provinces by source and year, 1995-2018, TWh (Authors' elaboration on data from China Energy Statistic Yearbook)

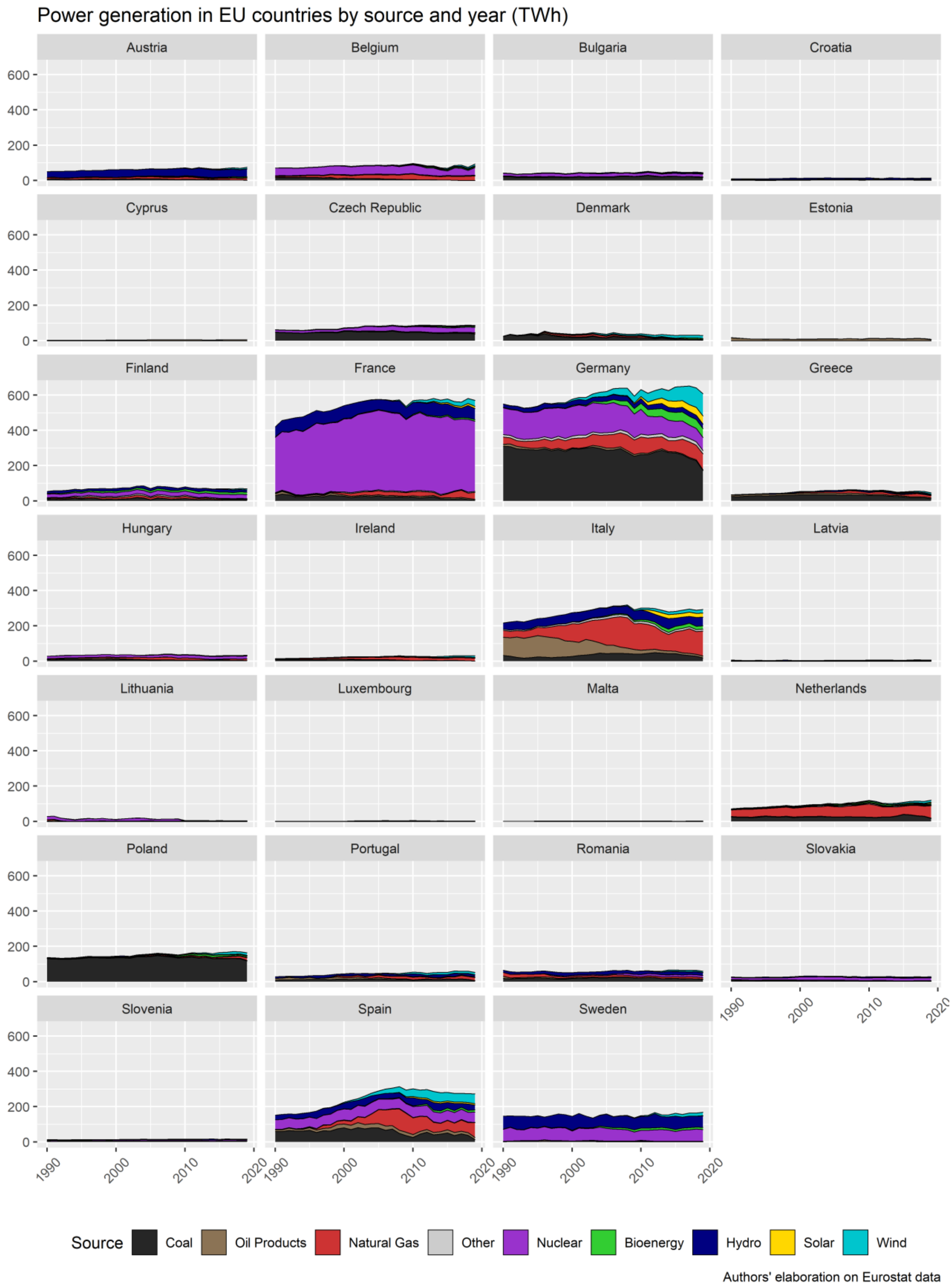

Figure 15 – Electricity generation in EU countries by source and year, 1990-2019, TWh (Authors' elaboration on Eurostat data)

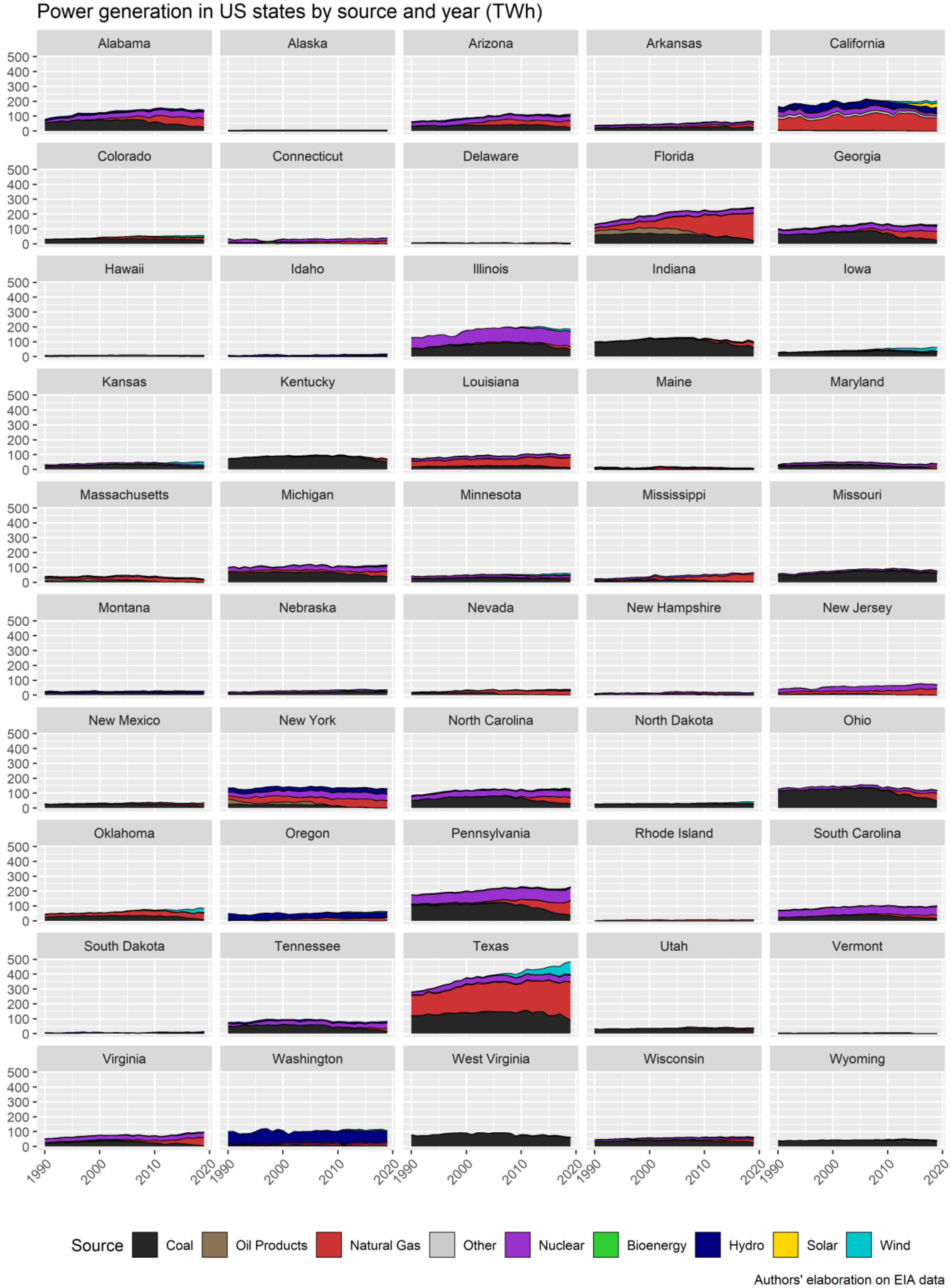

Figure 16 – Electricity generation in US states by source and year, 1990-2019, TWh (Authors' elaboration on EIA data).

Table 2 – Electricity generation in Chinese provinces in 2018, sorted by largest electricity producer.

Order	Province	Energy (TWh)	Share of Chinese total	Cumulative Share	Fossil	Nuclear	RES
1	Shandong	591.8	8%	8%	93%	1%	6%
2	Jiangsu	514.6	7%	15%	89%	5%	6%
3	Inner Mongolia	496.1	7%	22%	84%	0%	16%
4	Guangdong	471.6	7%	29%	74%	19%	8%
5	Sichuan	369.3	5%	34%	12%	0%	88%
6	Zhejiang	349.3	5%	39%	74%	17%	9%
7	Xinjiang	330.6	5%	44%	78%	0%	22%
8	Yunnan	324.2	5%	48%	9%	0%	91%
9	Hebei	322.9	5%	53%	87%	0%	13%
10	Shanxi	320.3	4%	57%	89%	0%	11%
11	Henan	306.0	4%	61%	91%	0%	9%
12	Hubei	281.7	4%	65%	44%	0%	56%
13	Anhui	274.1	4%	69%	92%	0%	8%
14	Fujian	247.9	3%	73%	56%	26%	18%
15	Guizhou	202.1	3%	75%	60%	0%	40%
16	Liaoning	198.6	3%	78%	73%	15%	12%
17	Shaanxi	192.0	3%	81%	85%	0%	15%
18	Guangxi	173.2	2%	83%	47%	9%	43%
19	Ningxia	167.2	2%	86%	82%	0%	18%
20	Hunan	154.0	2%	88%	60%	0%	40%
21	Gansu	154.0	2%	90%	52%	0%	48%
22	Jiangxi	128.6	2%	92%	83%	0%	17%
23	Heilongjiang	104.7	1%	93%	84%	0%	16%
24	Jilin	86.9	1%	94%	78%	0%	22%
25	Shanghai	84.8	1%	96%	97%	0%	3%
26	Chongqing	81.2	1%	97%	67%	0%	33%
27	Qinghai	81.1	1%	98%	15%	0%	85%
28	Tianjin	72.5	1%	99%	98%	0%	2%
29	Beijing	45.1	1%	99%	96%	0%	4%
30	Hainan	32.5	0%	100%	65%	24%	11%
31	Xizang	6.9	0%	100%	4%	0%	96%

Table 3 – Electricity generation in EU Countries in 2019, sorted by largest electricity producer.

Order	Country	Energy (TWh)	Share of EU total	Cumulative Share	Fossil	Nuclear	RES
1	Germany	607.6	21%	21%	47%	12%	41%
2	France	570.3	20%	41%	9%	70%	21%
3	Italy	293.2	10%	51%	62%	0%	38%
4	Spain	273.1	9%	60%	41%	21%	38%
5	Sweden	168.4	6%	66%	2%	39%	59%
6	Poland	163.8	6%	72%	84%	0%	16%
7	Netherlands	120.4	4%	76%	78%	3%	19%
8	Belgium	93.3	3%	79%	31%	47%	22%
9	Czech Republic	86.9	3%	82%	52%	35%	13%
10	Austria	74.2	3%	85%	22%	0%	78%
11	Finland	68.4	2%	87%	18%	35%	47%
12	Romania	59.6	2%	89%	39%	19%	42%
13	Portugal	53.2	2%	91%	46%	0%	54%
14	Greece	45.5	2%	92%	64%	0%	36%
15	Bulgaria	44.3	2%	94%	45%	37%	18%
16	Hungary	34.0	1%	95%	38%	48%	14%
17	Ireland	30.9	1%	96%	61%	0%	39%
18	Denmark	29.5	1%	97%	22%	0%	78%
19	Slovakia	28.4	1%	98%	22%	54%	24%
20	Slovenia	16.1	1%	99%	31%	36%	33%
21	Croatia	12.8	0%	99%	34%	0%	66%
22	Estonia	7.6	0%	99%	72%	0%	28%
23	Latvia	6.4	0%	100%	50%	0%	50%
24	Cyprus	5.1	0%	100%	90%	0%	10%
25	Lithuania	3.7	0%	100%	18%	0%	82%
26	Malta	2.1	0%	100%	89%	0%	11%
27	Luxembourg	1.9	0%	100%	14%	0%	86%

Table 4 – Electricity generation in US States in 2019, sorted by largest electricity producer.

Order	Name	Energy (TWh)	Share of US total	Cumulative Share	Fossil	Nuclear	RES
1	Texas	483.2	12%	12%	73%	9%	19%
2	Florida	245.6	6%	18%	85%	12%	3%
3	Pennsylvania	229.0	6%	23%	60%	36%	4%
4	California	201.8	5%	28%	49%	8%	43%
5	Illinois	184.5	4%	33%	38%	54%	8%
6	Alabama	142.7	3%	36%	59%	31%	11%
7	New York	131.6	3%	39%	38%	34%	28%
8	North Carolina	131.2	3%	42%	55%	32%	13%
9	Georgia	128.7	3%	46%	65%	26%	9%
10	Ohio	120.0	3%	48%	83%	14%	3%
11	Michigan	116.7	3%	51%	64%	28%	8%
12	Arizona	113.6	3%	54%	61%	28%	11%
13	Washington	106.5	3%	57%	22%	8%	70%
14	Indiana	102.5	2%	59%	93%	0%	7%
15	Louisiana	100.2	2%	61%	82%	14%	4%
16	South Carolina	100.1	2%	64%	39%	56%	6%
17	Virginia	96.8	2%	66%	64%	30%	6%
18	Oklahoma	85.2	2%	68%	61%	0%	39%
19	Tennessee	82.3	2%	70%	43%	43%	14%
20	Missouri	78.3	2%	72%	81%	12%	7%
21	Kentucky	71.8	2%	74%	94%	0%	6%
22	New Jersey	71.0	2%	76%	60%	37%	3%
23	Mississippi	66.0	2%	77%	81%	17%	3%
24	Arkansas	64.4	2%	79%	70%	21%	9%
25	West Virginia	63.9	2%	80%	95%	0%	5%
26	Wisconsin	62.8	2%	82%	75%	16%	9%
27	Iowa	62.6	2%	83%	48%	8%	44%
28	Oregon	62.3	2%	85%	38%	0%	62%
29	Minnesota	59.4	1%	86%	52%	24%	24%
30	Colorado	56.3	1%	88%	75%	0%	25%
31	Kansas	50.9	1%	89%	40%	18%	42%
32	Wyoming	42.1	1%	90%	87%	0%	13%
33	North Dakota	41.1	1%	91%	65%	0%	35%
34	Connecticut	40.1	1%	92%	55%	42%	3%
35	Nevada	39.9	1%	93%	81%	0%	19%
36	Maryland	39.3	1%	94%	53%	38%	9%
37	Utah	39.1	1%	95%	90%	0%	10%
38	Nebraska	37.3	1%	96%	58%	19%	23%
39	New Mexico	35.2	1%	97%	76%	0%	24%
40	Montana	27.8	1%	97%	55%	0%	45%

Order	Name	Energy (TWh)	Share of US total	Cumulative Share	Fossil	Nuclear	RES
41	Massachusetts	21.5	1%	98%	75%	10%	15%
42	Idaho	18.4	0%	98%	24%	0%	76%
43	New Hampshire	18.0	0%	99%	22%	61%	17%
44	South Dakota	14.5	0%	99%	26%	0%	74%
45	Maine	10.5	0%	99%	21%	0%	79%
46	Hawaii	9.7	0%	99%	88%	0%	12%
47	Rhode Island	7.6	0%	100%	94%	0%	6%
48	Alaska	6.1	0%	100%	70%	0%	30%
49	Delaware	5.3	0%	100%	98%	0%	2%
50	Vermont	2.3	0%	100%	0%	0%	100%

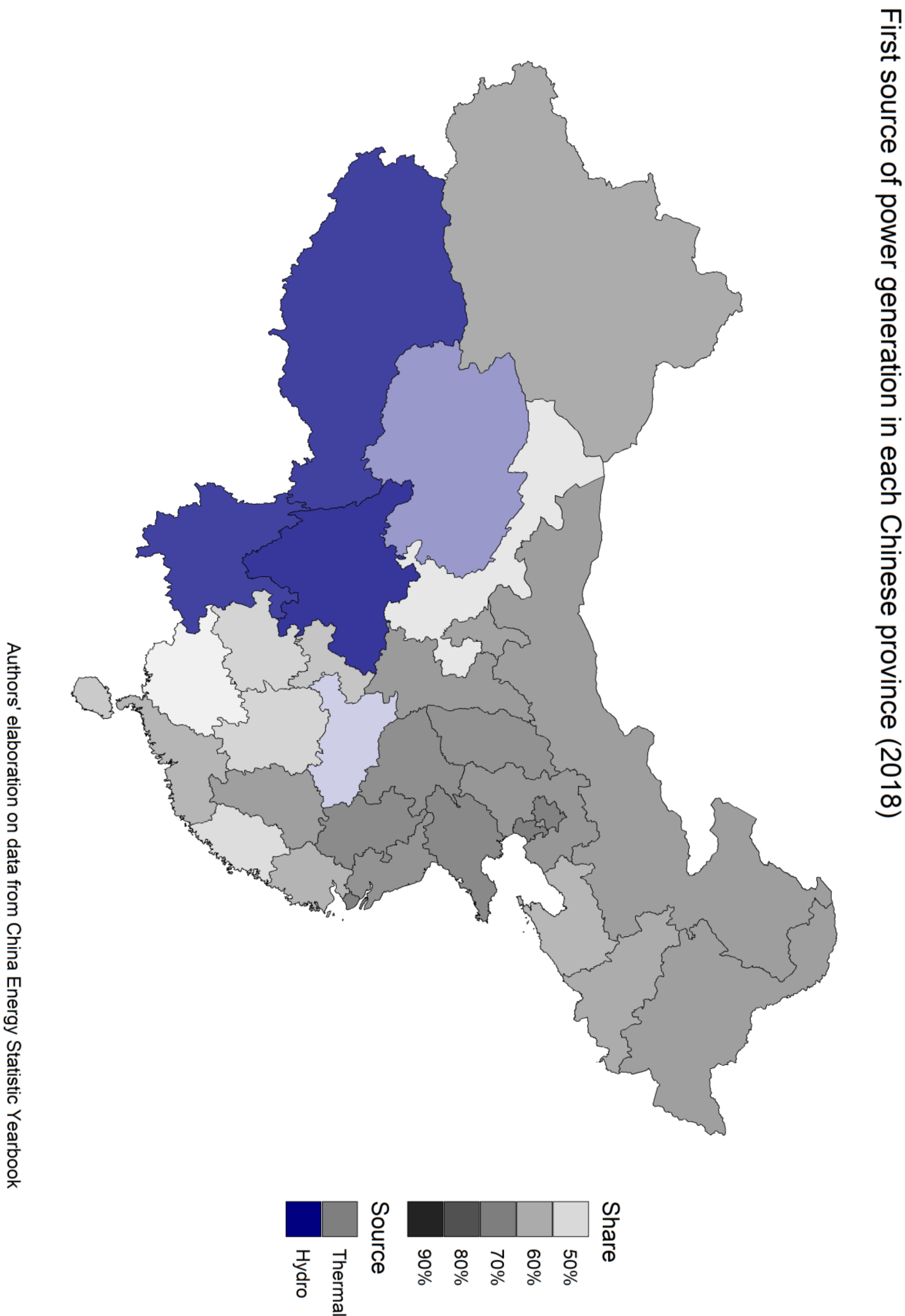

Figure 17 – Map of first source of power generation in each Chinese province.

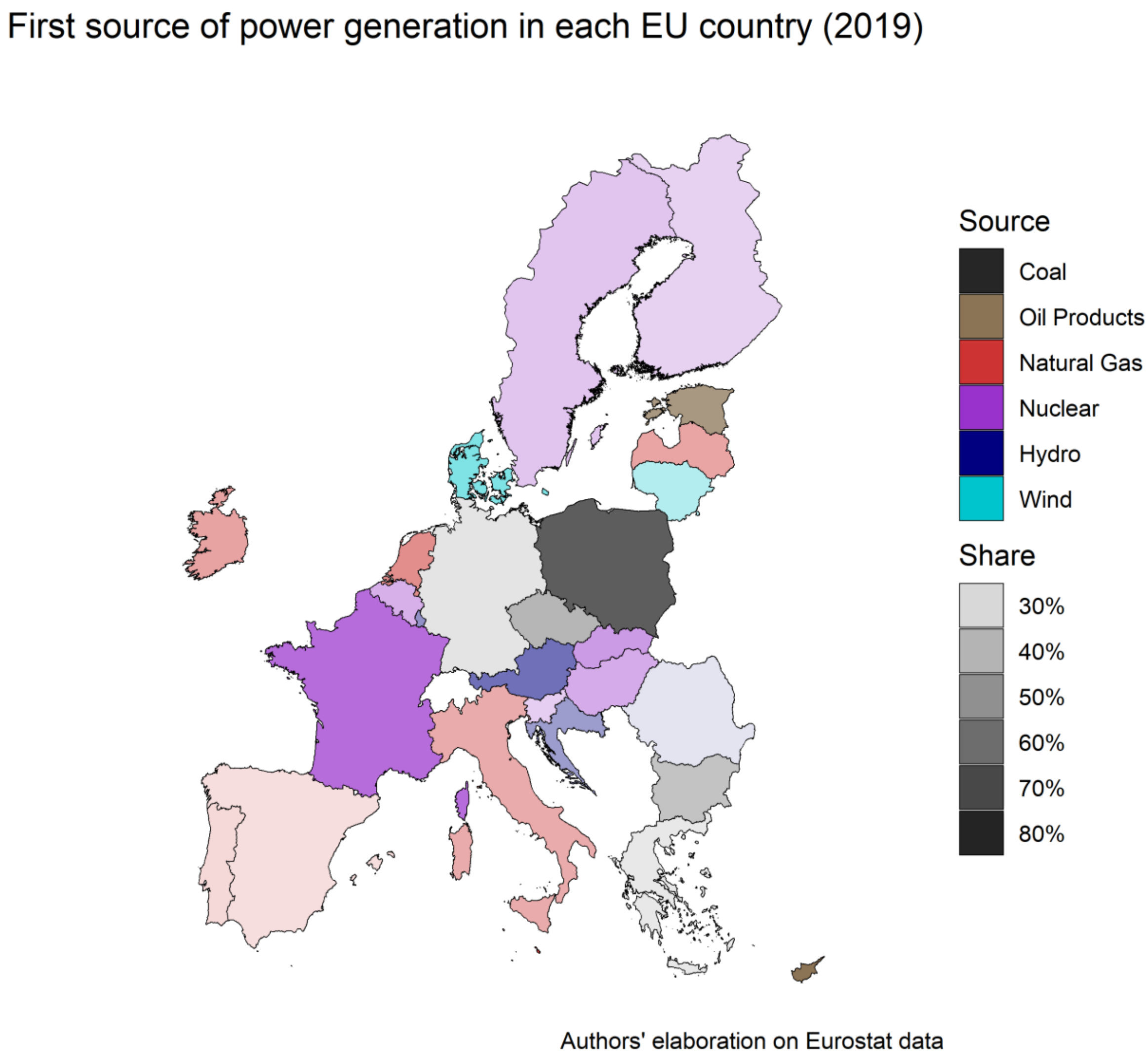

Figure 18 – Map of first source of power generation in each EU country.

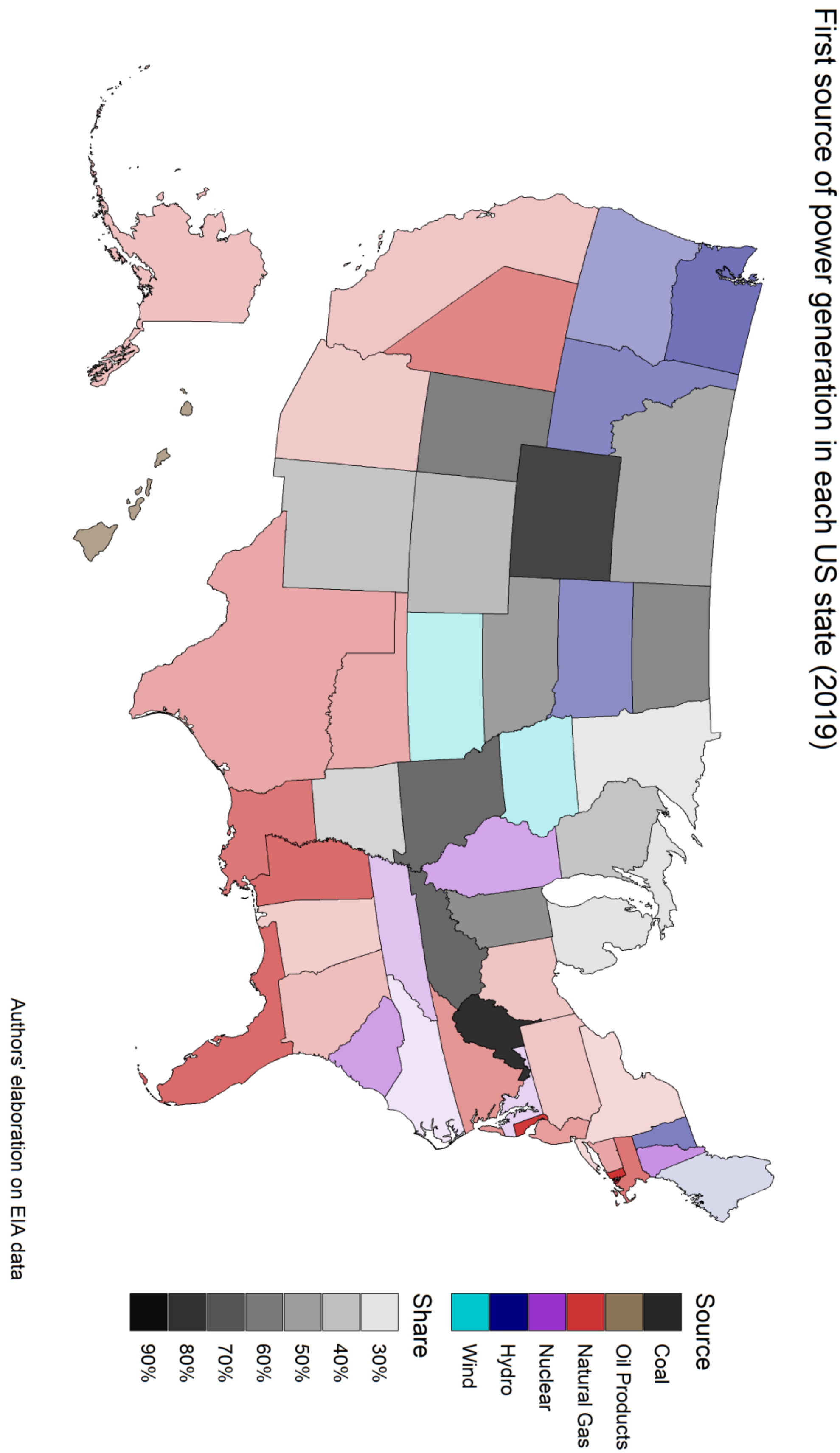

Figure 19 – Map of first source of power generation in each US state.

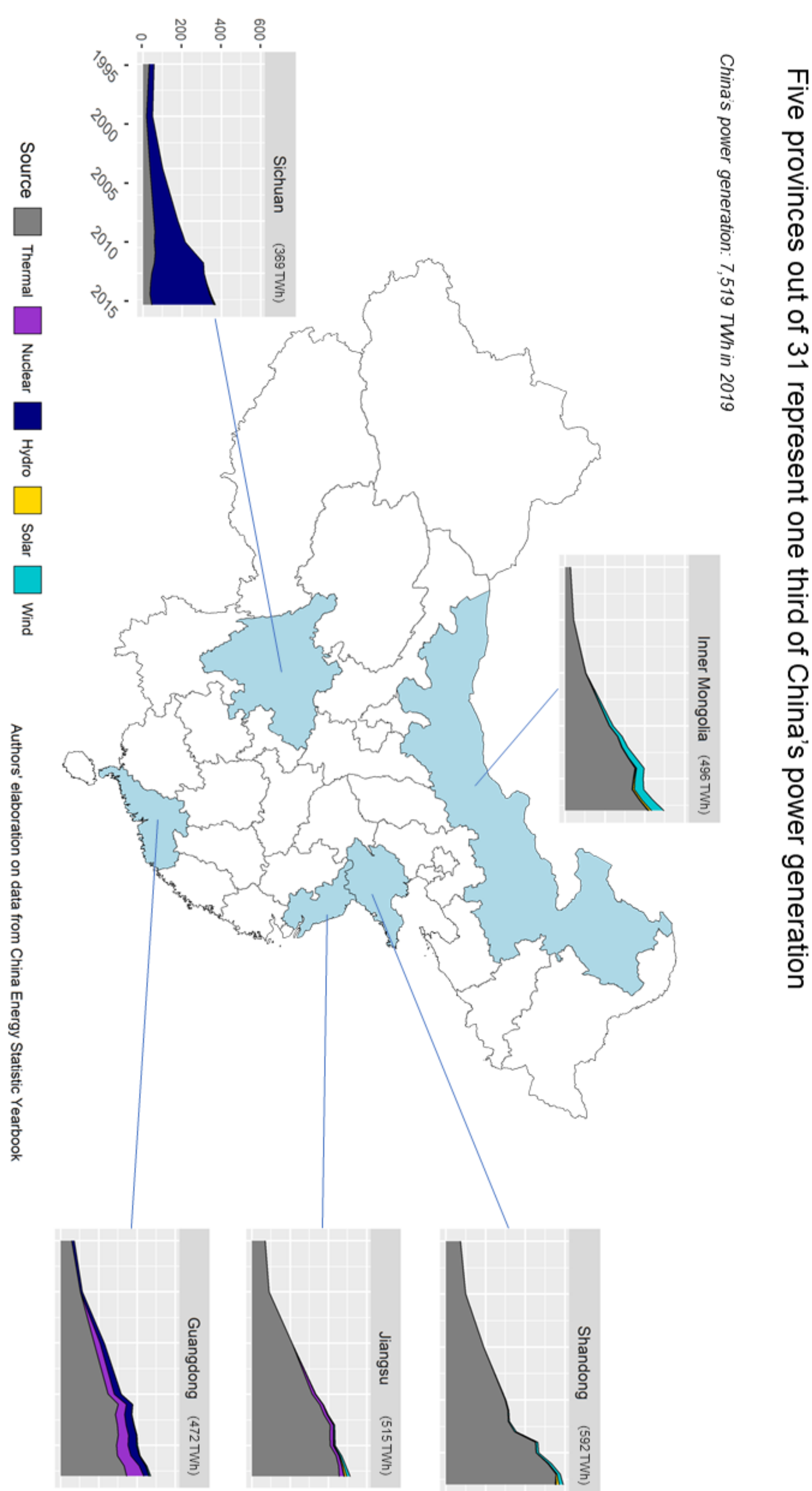

Figure 20 – Map of the electricity mixes of the main Chinese provinces for electricity generation.

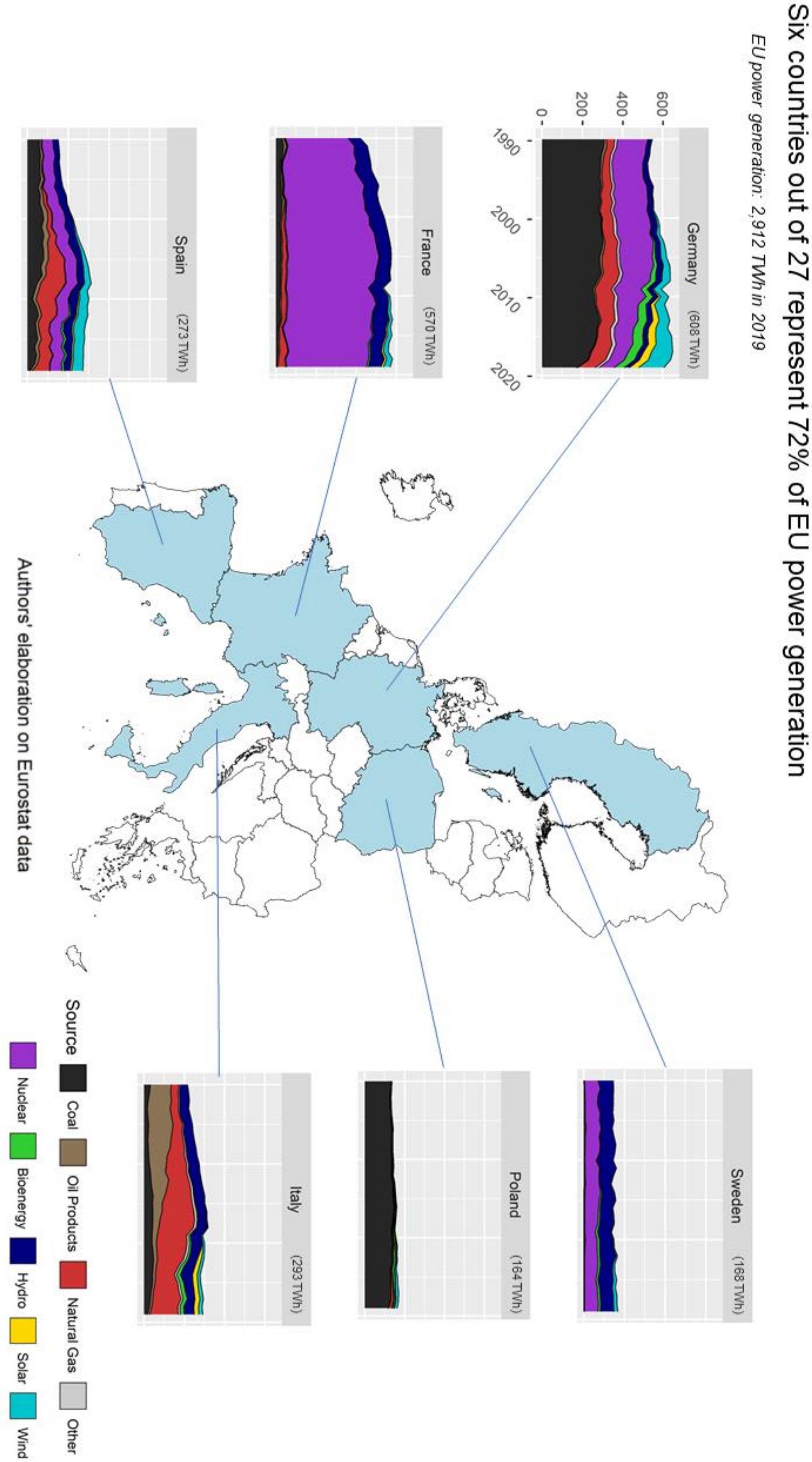

Figure 21 – Map of the electricity mixes of the main EU countries for electricity generation.

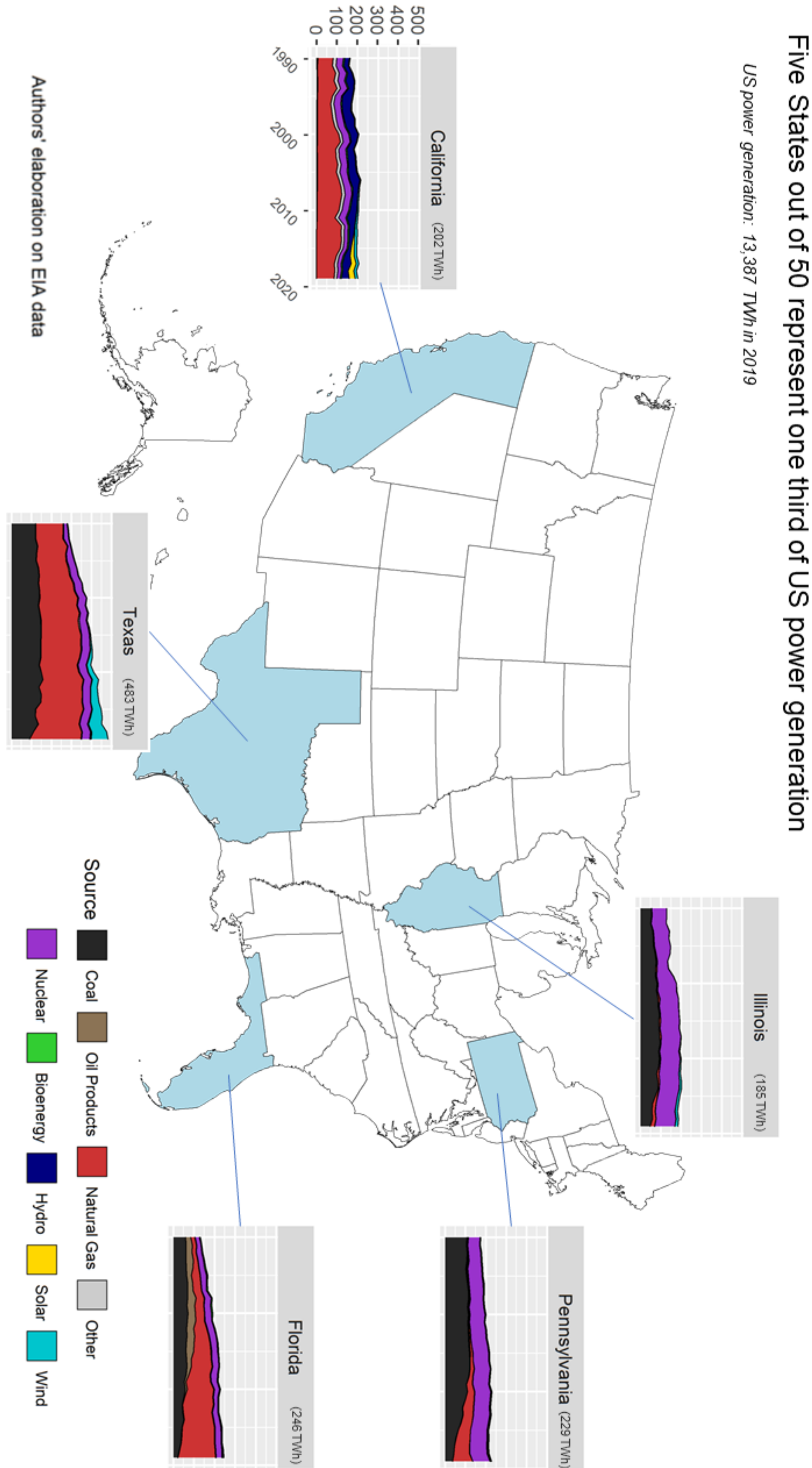

Figure 22 – Map of the electricity mixes of the main US states for electricity generation.

Figure 23 – Map of Chinese provinces (source: Wikipedia).

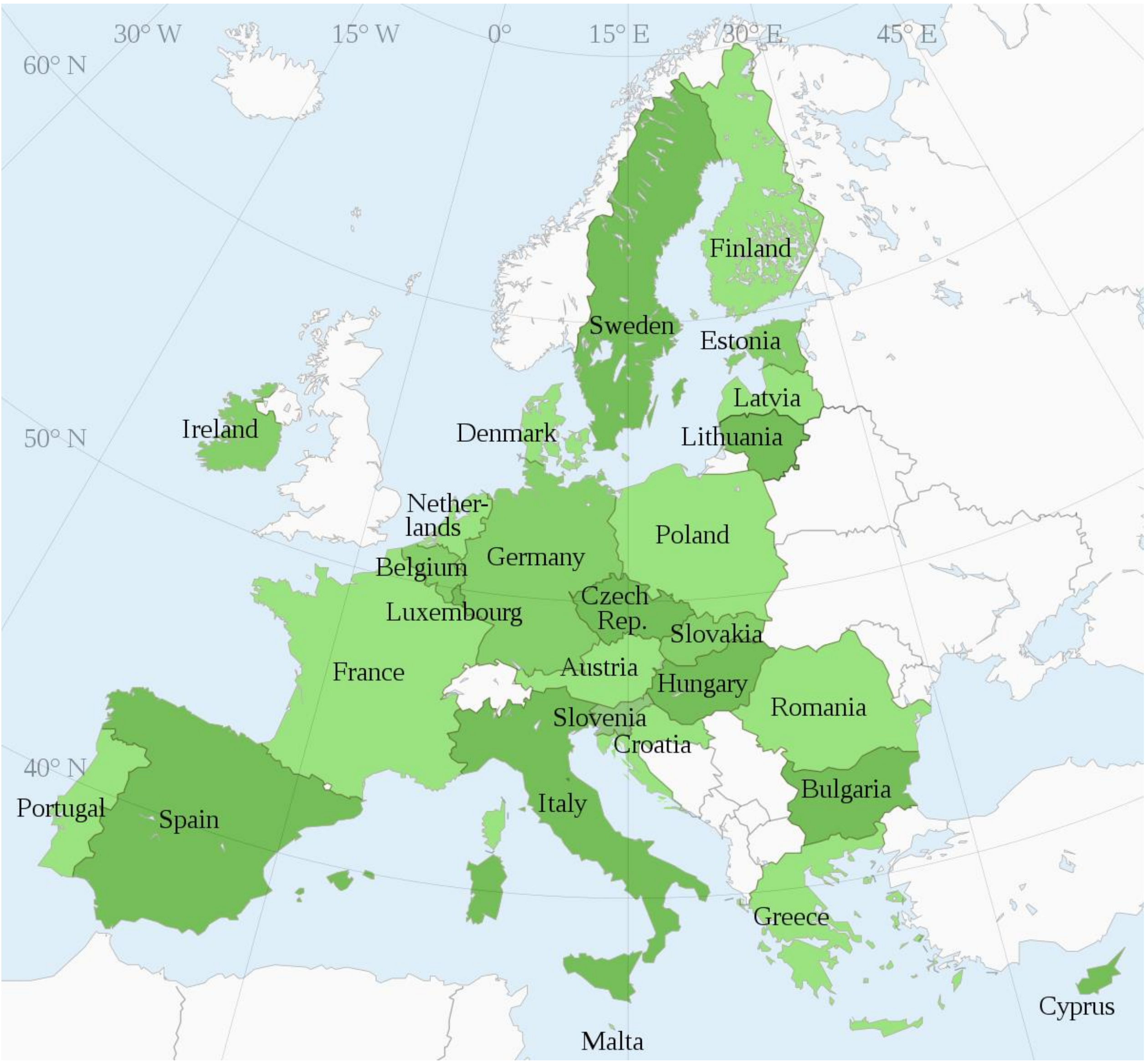

Figure 24 – Map of EU member states (source: Wikipedia).

Figure 25 – Map of US states (source: Wikipedia).

FONDAZIONE ENI ENRICO MATTEI WORKING PAPER SERIES
"NOTE DI LAVORO"
Our Working Papers are available on the Internet at the following address:
http://www.feem.it/getpage.aspx?id=73&sez=Publications&padre=20&tab=1

"NOTE DI LAVORO" PUBLISHED IN 2021

1. 2021, Alberto Arcagni, Laura Cavalli, Marco Fattore, Partial order algorithms for the assessment of italian cities sustainability
2. 2021, Jean J. Gabszewicz, Marco A. Marini, Skerdilajda Zanaj, Random Encounters and Information Diffusion about Product Quality
3. 2021, Christian Gollier, The welfare cost of ignoring the beta
4. 2021, Richard S.J. Tol, The economic impact of weather and climate
5. 2021, Giacomo Falchetta, Nicolò Golinucci, Michel Noussan and Matteo Vincenzo Rocco, Environmental and energy implications of meat consumption pathways in sub-Saharan Africa
6. 2021, Carlo Andrea Bollino, Marzio Galeotti, On the water-energy-food nexus: Is there multivariate convergence?
7. 2021, Federica Cappelli, Gianni Guastella, Stefano Pareglio, Urban sprawl and air quality in European Cities: an empirical assessment
8. 2021, Paolo Maranzano, Joao Paulo Cerdeira Bento, Matteo Manera, The Role of Education and Income Inequality on Environmental Quality. A Panel Data Analysis of the EKC Hypothesis on OECD
9. 2021, Iwan Bos, Marco A. Marini, Riccardo D. Saulle, Myopic Oligopoly Pricing
10. 2021, Samir Cedic, Alwan Mahmoud, Matteo Manera, Gazi Salah Uddin, Information Diffusion and Spillover Dynamics in Renewable Energy Markets
11. 2021, Samir Cedic, Alwan Mahmoud, Matteo Manera, Gazi Salah Uddin, Uncertainty and Stock Returns in Energy Markets: A Quantile Regression Approach
12. 2021, Sergio Tavella, Michel Noussan, The potential role of hydrogen towards a low-carbon residential heating in Italy
13. 2021, Maryam Ahmadi, Matteo Manera, Oil Prices Shock and Economic Growth in Oil Exporting Countries
14. 2021, Antonin Pottier, Emmanuel Combet, Jean-Michel Cayla, Simona de Lauretis, Franck Nadaud, Who emits CO_2? Landscape of ecological inequalities in France from a critical perspective
15. 2021, Ville Korpela, Michele Lombardi, Riccardo D. Saulle, An Implementation Approach to Rotation Programs
16. 2021, Miguel Borrero, Santiago J. Rubio, An Adaptation-Mitigation Game: Does Adaptation Promote Participation in International Environmental Agreements?
17. 2021, Alan Finkelstein Shapiro, Gilbert E. Metcalf, The Macroeconomic Effects of a Carbon Tax to Meet the U.S. Paris Agreement Target: The Role of Firm Creation and Technology Adoption
18. 2021, Davide Bazzana, Jeremy Foltz, Ying Zhang, Impact of climate smart agriculture on food security: an agent-based analysis
19. 2021, Chiara Casoli, Riccardo (Jack) Lucchetti, Permanent-Transitory decomposition of cointegrated time series via Dynamic Factor Models, with an application to commodity prices
20. 2021, Pauline Pedehour, Lionel Richefort, Empowerment of social norms on water consumption
21. 2021, Carlo Drago, The Analysis and the Measurement of Poverty: An Interval-Based Composite Indicator Approach
22. 2021, Davide Bazzana, Francesco Menoncin, Sergio Veralli, The day after tomorrow: mitigation and adaptation policies to deal with uncertainty
23. 2021, Liang Nie, ZhongXiang Zhang, Is high-speed green? Evidence from a quasi-natural experiment in China
24. 2021, Michel Noussan, Manfred Hafner, Loyle Campbell, Xinqing Lu, Pier Paolo Raimondi, Erpu Zhu, Towards the decarbonization of the power sector – a comparison of China, the EU and the US based on historical data

Fondazione Eni Enrico Mattei
Corso Magenta 63, Milano – Italia

Tel. +39 02.520.36934
Fax. +39.02.520.36946

E-mail: letter@feem.it
www.feem.it

Fondazione Eni Enrico Mattei