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# Transitioning to A Sustainable Society

## Essays in Environmental and Urban Economics

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# Transitioning to A Sustainable Society: Essays in Environmental and Urban Economics


## Abstract

Both environmental and social sustainability are key to building a sustainable society. This thesis contains five empirical papers that investigate different aspects of sustainability in Swedish society.

Paper 1 uses comprehensive geocoded population data to explore socioeconomic inequality in exposure to air pollution of toxic metals across Sweden. We find no evidence of environmental inequality in Sweden since the 1990s.

Paper 2 explores how extreme weather events influenced by climate change, like the 2018 Swedish forest fires, shape individuals' environmental beliefs. The findings suggest that such events could heighten political polarization in environmental attitudes.

Paper 3 assesses the functioning of the Swedish electricity intraday market, in light of the supply and price variability induced by an increasing share of wind power. The results indicate that the intraday market is functioning properly.

Paper 4 investigates the effects of implementing apartment-level metering for residential hot water consumption in multi-family buildings. Our findings demonstrate that consumption is 18% lower when tenants pay for their own usage, compared to when they pay a fixed water fee.

Paper 5 uses Swedish population data to study the effects of income inequality on income-based residential segregation. We find that redistribution from the rich to the poor through taxes and transfers does not affect their choices to live in separate neighbourhoods.



Keywords: Environmental inequality, Climate events, Political polarization, Intraday market, Water conservation, Residential segregation.

# Hållbar samhällsutveckling: Uppsatser i miljö- och urbanekonomi

## Sammanfattning

Att främja miljömässig och social hållbarhet är viktigt för övergången till ett hållbart samhälle. Denna avhandling innehåller fem empiriska uppsatser som undersöker hållbarhetsfrågor i Sverige.

Uppsats 1 använder omfattande geografiskt kodade befolkningsdata för att utforska socioekonomisk ojämlikhet i exponering av luftburna tungmetallföroreningar i Sverige. Vi finner inga bevis för miljömässig ojämlikhet i Sverige sedan 1990-talet.

Uppsats 2 utforskar hur extrema händelser till följd av klimatförändringar, såsom de svenska skogsbränderna 2018, påverkar individers miljöuppfattningar. Resultaten antyder att sådana händelser förstärker politisk polarisering i miljöattityder.

Uppsats 3 bedömer funktionaliteten i den svenska intradagsmarknaden för el givet större variation i utbud och pris i och med den ökande andelen vindkraft i systemet. Resultaten indikerar att intradagsmarknaden fungerar som den ska.

Uppsats 4 studerar effekterna av lägenhetsspecifika vattenmätare på varmvattenanvändningen i flerfamiljshus. Våra resultat visar att konsumtionen är 18% lägre när varje lägenhet betalar för sin egen användning jämfört med när de betalar en fast avgift.

Uppsats 5 använder svenska befolkningsdata för att studera effekterna av inkomstojämlikhet på inkomstbaserad bostadssegregation. Vi finner att omfördelning från rika till fattiga via skatter och bidrag inte motverkar att deras val att bo i olika grannskap.

Nyckelord: Miljömässig ojämlikhet, Klimatförändring, Politisk polarisering, Intradagsmarknaden, Vattenbesparing, Bostadssegregation

# Contents

# List of publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I. Oscar Erixson, Jakob Granath, Xiao Hu, and Mattias Öhman (2024). Toxic metal injustice? Socioeconomic status at birth and exposure to airborne pollution. Revisions requested by Journal of Urban Economics.

II. Xiao Hu (2024). Who is concerned about climate change when forests are burning? Evidence from Swedish forest fires. Manuscript.

III. Xiao Hu, Jūratė Jaraitė, and Andrius Kažukauskas (2021). The effects of wind power on electricity markets: A case study of the Swedish intraday market. Energy Economics, 96, 1051-1059.

IV. Mikael Elinder, Xiao Hu, Che-Yuan Liang, and Shane Minckley (2024). Mind the tap – how volumetric pricing affects residential hot water consumption. Revisions requested by Journal of the Association of Environmental and Resource Economists.

V. Xiao Hu and Che-Yuan Liang (2022). Does income redistribution prevent residential segregation? Journal of Economics Behavior and Organization, 193, 519-542

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The contribution of Xiao Hu to the papers included in this thesis was as follows:

I. I identified, gathered, and processed the emission and plant data used, conducted parts of the analysis, and wrote parts of the manuscript.

II. I am the sole author.

III. I conducted the analysis, wrote a first draft of the paper, and finalized the manuscript together with co-authors.

IV. I conducted parts of the estimations, implemented the cost-benefit analysis, and wrote parts of the manuscript.

V. I formulated the research idea, conducted parts of the analysis, and wrote parts of the manuscript.

# List of figures

# 1. Introduction

The world has been facing unprecedented environmental challenges, ranging from overexploitation of natural resources, air and water pollution, soil degradation, and biodiversity loss, to climate change. Economists suggest these issues arise due to negative externalities associated with production and consumption activities, attributing them to market failures. Economic development relies on natural resources and ecosystem services but adversely affects the environment in unsustainable ways as a consequence of these externalities. Several of the United Nations' 17 goals in their 2030 agenda for sustainable development are environmental objectives, such as climate action and clean energy. This thesis primarily explores two key environmental issues central to the sustainable development agenda: air pollution and climate change, both of which exert a significant influence on environmental quality and overall quality of life.

Worldwide, economic growth has been accompanied by urbanisation. While concentrated economic activities, specialisation, and agglomeration, make cities productive and urban areas attractive residential choices, densely populated urban areas also suffer from pollution and traffic congestion, among other environmental issues. With 88 percent of the Swedish population residing in urban areas in 2020, and one-third living in areas exceeding 100,000 inhabitants (Statistics Sweden, 2021), environmental problems affect the quality of life for a significant portion of the population. In this context, the fields of environmental and urban economics intertwine, since they involve investigating the causes and consequences of urban economic growth and exploring solutions to these challenges (Baum-Snow and Ferreira, 2015). Several papers in this thesis explore environmental topics with important spatial dimensions or of special relevance for urban areas.

In addition to environmental goals, the United Nation's sustainability goals promote social objectives, including the reduction of inequality, and the goal of sustainable cities and communities specifically focuses on urban areas. Urban growth is often associated with negative social externalities such as residential segregation, social exclusion, and greater crime, impacting residents' quality of life. One chapter in this thesis is devoted to the social challenge of residential segregation by income between neighbourhoods.

Whether environmental problems manifest in natural settings or urban areas, they often result from inappropriate use of resources, largely due to unpriced or underpriced resources. Government intervention is crucial for addressing these problems, with the key goal of incentivising firms and individuals to contribute to improving environmental quality. Similarly, public policy plays a key role in achieving social sustainability goals, and it is important to understand how these policies affect individual behaviours, such as residential choices.

This thesis contains five empirical papers exploring aspects of sustainability in Swedish society, covering both national-level environmental challenges and those specific to urban settings, with a dedicated paper on income-based residential segregation. The papers use a variety of data including individual-level full-population data over a long time period, survey data, data provided by firms and organizations, spatially coded bio-monitored data, and macro-level time-series data. All papers have policy implications, and several use quasi-experimental designs to provide causal evidence.

In this introductory chapter, I attempt to relate the different papers to a common institutional background. The focus is on environmental and (some) social issues Sweden faced over time, particularly the institutional responses they have triggered. Moreover, I discuss research relevant to the Swedish context, including but not limited to those based on Swedish data. The picture provided here is useful not only for understanding the broader context of different papers but also for relating them to each other. An ambition is to go beyond the institutional setting and research literature relevant to the papers and provide a broader and coherent picture useful for understanding Sweden's concurrent efforts in transitioning into a sustainable society. This means that while the thesis contains at least one paper relevant to every theme in this introduction, the exposition of a theme serves a purpose beyond merely introducing the relevant papers.

Four themes are relevant to this thesis: The first theme is air pollution and its impacts on health and residential sorting, which is relevant to Paper 1. The second theme concerns climate change and its effects on society, which is relevant to Paper 2. The third theme revolves around the energy transition, particularly focusing on the role of supply- and demand-side policies, and is relevant for Papers 3 and 4. The final theme pertains to a social sustainability issue, income-based residential segregation, and is relevant to Paper 5.

Regarding the papers, Paper 1 explores socioeconomic inequality in exposure to air pollution of toxic metals, and the findings suggest no environmental inequality in Sweden since the 1990s. Paper 2 investigates how extreme weather events affect individuals' environmental beliefs, revealing the importance of motivated reasoning in shaping such beliefs and suggesting that fires exacerbate political polarization in environmental attitudes. Paper 3 assesses the functioning of the Swedish electricity intraday market in light of the supply and price variability induced by an increasing share of wind power, concluding that the intraday market sends out correct price signals and functions properly. Paper 4 uses a quasi-experiment to study the impacts of apartment-level billing for residential hot water consumption, showing a significant 18% reduction in consumption when tenants pay for their usage, transitioning from a shared cost system. Paper 5 uses Swedish population data to study the causal effects of income inequality on residential income segregation across neighbourhoods in cities, and we find that more income redistribution cannot mitigate segregation.

My research provides grounds for both optimism and concern. It demonstrates the potential of a comprehensive policy approach to address significant environmental issues like environmental inequality. Additionally, it provides examples of both broad and specific policies that incentivize energy and resource conservation, crucial for a sustainable transition. However, my findings also shed light on a concerning trend: the increasing severity of environmental impacts, particularly those stemming from climate change, may impede rather than facilitate this transition. Instead of observing widespread shifts towards environmental consciousness and unified support for climate policies, my research suggests a potential escalation of social tension. Furthermore, some of my research indicates that social challenges, whether environmental or not, may not have straightforward solutions.

The remainder of this introductory chapter is organized as follows: Section 2 provides the institutional background and a literature review, while Section 3 offers a summary of each essay.

# 2. Institutional background and literature review

## 2.1 Air pollution

The relationship between economic growth and environmental quality is complex. Incorporating pollution as a by-product and source of disutility in growth models, theoretical work suggests a nonlinear relationship between GDP per capita and pollution (Xepapadeas, 2005). Empirical research has estimated this relationship (Grossman and Krueger, 1995; Harbaugh et al., 2002; Carson, 2010). According to the environmental Kuznets curve (EKC) hypothesis, environmental quality initially deteriorates with growth. However, once societies reach a certain income level, economic growth is associated with environmental progress since wealthier people may prefer cleaner products, residential areas, and workplaces, and for these reasons, they are likely to support stringent environmental regulations.

Figure 1 illustrates the Swedish development of per capita GDP and emissions of nitrogen oxides ($NO_x$) and sulphur dioxide ($SO_2$) from 1834 to 2018. While GDP exhibits an increasing trend, emissions rose before the 1970s and declined thereafter. Figure 2 depicts the relationship, indicating a bell-shaped curve with turning points located around $20,000 for sulphur dioxide and $25,000 for nitrogen oxides. While the figure is in line with the EKC hypothesis for air pollution in Sweden, the evidence should not be interpreted causally.

Whether economic growth eventually has positive effects on environmental quality remains debatable; however, in most countries, environmental progress is closely tied to regulations, investments, and efforts to improve environmental quality (Carson, 2010). Influenced by Rachel Carson's 1962 book Silent Spring and growing public concerns about the environment, the Swedish Environmental Protection Agency was established in 1967 and the Environment Protection Act was enacted in 1969 (Lundqvist, 1972). These events coincide with the turning point in Sweden's EKC curves (Figure 2). In the following decades, a series of environmental policies were implemented, and a significant decline in air pollution levels followed (Figure 1).

In response to industrial pollution, Sweden has implemented a range of pollution control measures and policies aimed at incentivizing manufacturing firms to adopt cleaner technologies. These interventions target the reduction of air pollutants and greenhouse gases like nitrogen oxides, sulphur dioxide, particulate matter, etc. (Coria, 2021; Ustyuzhanina, 2022). Many of the pollutants could pose health risks such as respiratory diseases and cancer. Epidemiological studies using Swedish data have documented an association between industrial pollution and human health (Victorin, 1993).

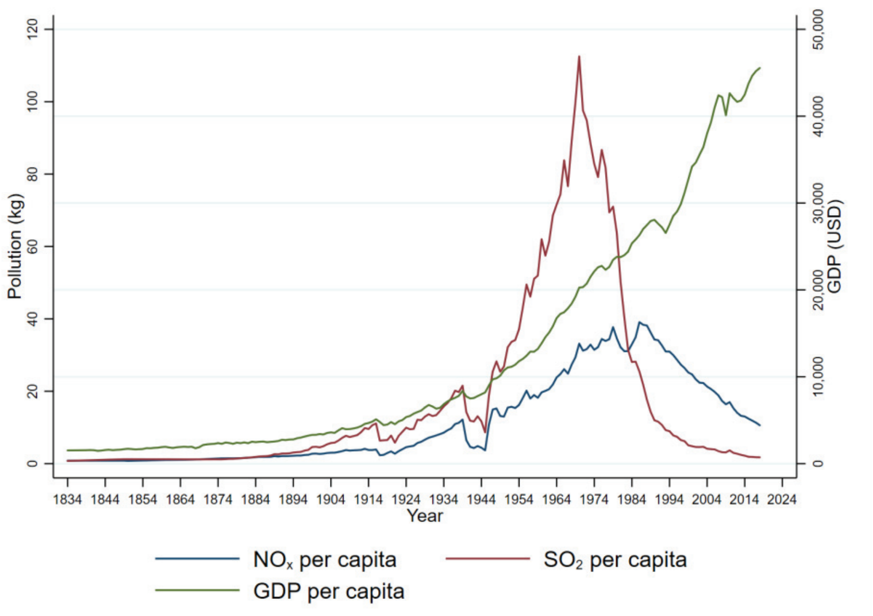


Figure 1. GDP, $NO_x$, and $SO_2$ per capita in Sweden since 1834

Note: All monetary measures are expressed in USD at the 2011 price level. The data are sourced from the Maddison Project Database 2020 (Bolt and van Zanden, 2020) and the Community Emissions Data System (CEDS), and processed by Our World in Data.

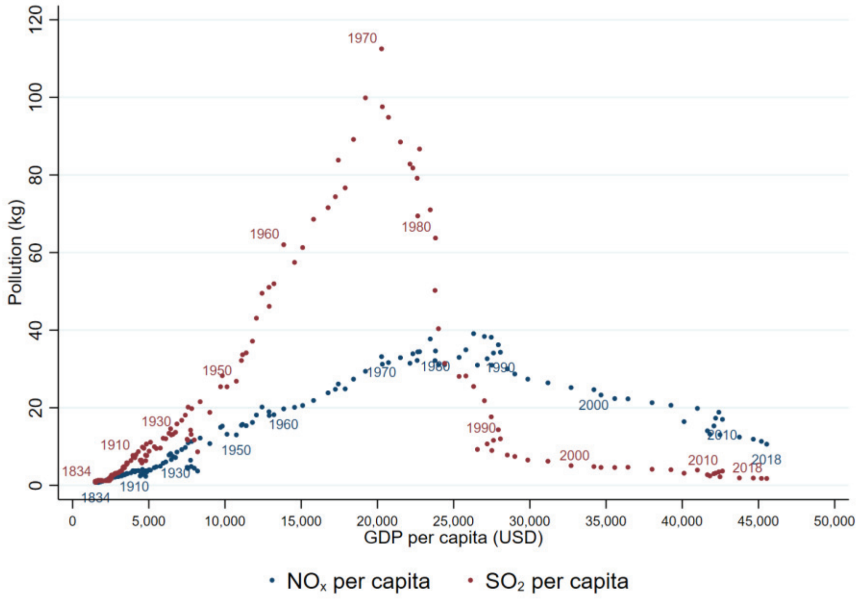


Figure 2. Environmental Kuznets curves of $NO_x$ and $SO_2$ in Sweden

Note: The data are from the same sources as in Figure 1.

In urban areas, factors like increased car use, commuting, and concentrated industrial activities contribute to urban air pollution. Environmental and urban economists have empirically studied the effects of air pollution on human health and urban life. In a historical context, the industrial and residential use of coal in the UK led to increased infant mortality rates (Beach and Hanlon, 2017), reduced long-term employment and population growth in cities (Hanlon, 2019), and influenced the spatial structure of cities persisting to the present day (Heblich et al., 2021).

Substantial efforts have been underway, spanning many decades, to improve urban air quality and urban quality of life more broadly. Over recent decades, urban air quality has significantly improved in developed countries like the U.S. and European countries. Research conducted in the Swedish context has investigated the health effects of policy-induced reduction in air pollution. For instance, before 1970, lead air pollution was high in urban areas due to the use of leaded gasoline. The phaseout of leaded gasoline between 1970 and 1981 resulted in improved academic achievement, reduced crime, and better long-run outcomes (Grönqvist, et al., 2020).

Mitigating congestion in cities through measures like road pricing and congestion tolls also has potential benefits for air quality and public health (Currie and Walker, 2011). In 2006, Sweden introduced a congestion tax pilot program in Stockholm, later made permanent. In 2013, a similar program was implemented in Gothenburg. Studies show that these congestion taxes effectively reduced traffic (Börjesson and Kristoffersson, 2018), improved air quality, and contributed to a decline in childhood asthma cases (Simeonova et al., 2019).

An environmental policy could have positive environmental and health effects, but it is also important to understand its social consequences for the evaluation of its suitability. For instance, congestion taxes may affect the housing market and residential sorting. Anecdotal evidence suggests that the introduction of congestion pricing in Stockholm has enhanced the attractiveness of areas along commuting lines in suburban Stockholm, incentivizing developers to invest in these regions and accelerating suburbanisation. This is an interesting topic for future research.

Despite significant reductions in air pollution, concerns remain regarding long-term exposure to low levels of pollutants. Moreover, air pollution is unevenly distributed across space, influenced by and influencing the spatial structure of cities. Recent studies explore the impacts of air pollution on residential sorting, revealing that low-income and ethnic groups are disproportionately affected (Ard, 2015, Sun et al., 2017). Environmental policies have the potential to mitigate this inequality, as evidenced by the decline in the divergence of PM 2.5 exposure between Black and White populations in the U.S. due to the Clean Air Act (Currie et al., 2023).

Traditionally, economists have studied household sorting across areas based on their incomes and preferences for housing standards, local public goods (such as pollution, congestion, school quality, etc.), neighbour characteristics, and commuting opportunities (Kuminoff et al., 2013). Recent literature suggests that parents actively select high-quality neighbourhoods for their children (Chetty and Hendren, 2018; Heckman and Landersøb, 2022). However, limited evidence exists on whether parents select areas with better physical environments to avoid air pollution.

The first paper of this thesis leverages the depth of Swedish administrative and pollution data to explore the association between families' socioeconomic status and exposure to airborne pollution of toxic metals in their residential areas, focusing on the exposure of newborn children and pregnant women's moving patterns to avoid exposure. We find that children from families with different SES at the time of birth are evenly distributed across Sweden with regard to exposure to airborne pollution of arsenic, lead, and mercury and that the pattern is similar over three decades. The findings suggest no socioeconomic inequality in exposure to air pollution of toxic metals across the Swedish population at birth since the 1990s.

Importantly, our results do not downplay the potential consequence associated with airborne pollution of toxic metal. Instead, they lay the groundwork for future studies aiming to estimate the causal effects of exposure to toxic metals over the life-cycle. Moreover, from an international perspective, our results show that the severity of environmental inequalities following economic progress varies depending on the context but can potentially be alleviated. Nonetheless, further research is needed to assess the efficacy, efficiency, and distributional impacts of various policies, as well as to identify the most suitable policy combinations for different scenarios.

## 2.2 Climate change

Richer countries exhibit a higher demand for resource-intensive goods, transportation, energy, and water, consequently leading to increased greenhouse gas emissions (Parikh and Shukla, 1995). This raises the question of whether the environmental Kuznets curve (EKC) hypothesis that economic growth eventually mitigates environmental problems applies to greenhouse gas emissions. Even among rich countries, there is scant evidence of a significant reduction in $CO_2$ emissions. Kahn (2006) argues that the turning point for environmental issues that affect local communities, such as air pollution, occurs at lower income levels. This is likely driven by strong local support for environmental regulations from residents directly exposed to environmental problems. However, for greenhouse gas emissions, which involve large externalities, governments lack incentives to reduce emissions, creating a "tragedy of the commons" where countries free-ride on global mitigation efforts. Consequently, the turning points for these emissions, if such exist, are likely located at higher income levels.

Figure 3 plots the relationship between the Swedish GDP and $CO_2$ emissions per capita. Emissions have risen alongside GDP since 1834, reaching a turning point in the 1970s with income per capita at $20,000. This turning point aligns with those observed for nitrogen oxides and sulphur dioxide, suggesting that environmental regulations implemented since the 1970s have had impacts on both air pollution and greenhouse gas emissions. This positions Sweden as one of the early countries to reach an EKC turning point for $CO_2$ emission. Sweden's trajectory provides valuable insights into the effectiveness of environmental policies.

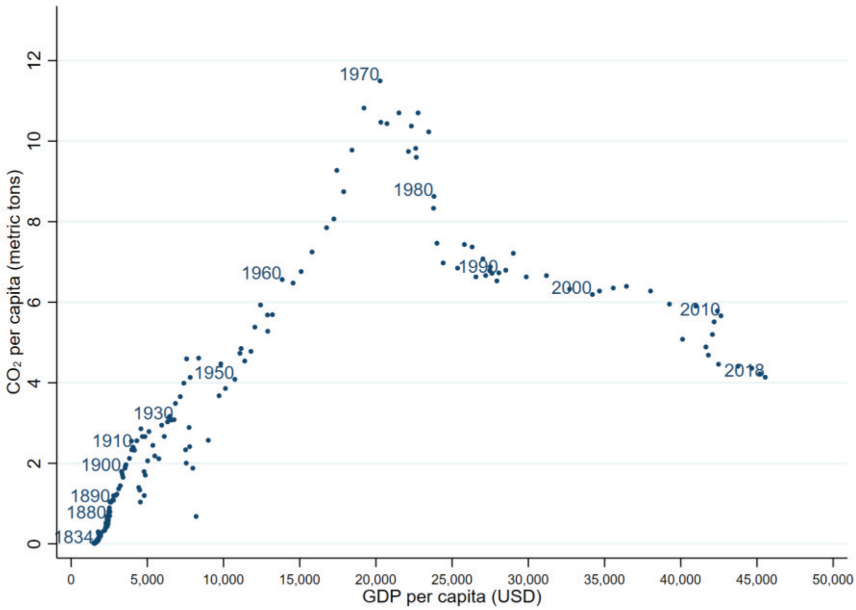


Figure 3. Environmental Kuznets curve of $CO_2$ in Sweden

Note: Data are from the same source as in Figure 1.

Sweden has the ambitious target of reaching net zero emissions of greenhouse gases by 2045 and contributing to global mitigation efforts. The various environmental measures employed include energy and carbon taxes, a compulsory blending of biofuel in transport fuels, and the Climate Stride scheme (Klimatklivet) that funds local and regional climate investments. Assessing the policy impacts is challenging and only a handful of studies have evaluated the effects on $CO_2$ emissions (Andersson, 2019; Gren and Tirkaso, 2021). But most likely, the entire package of policies has contributed to the decline of $CO_2$ in Sweden over time. However, maintaining a stable climate requires global efforts and is a shared responsibility among all nations. The absence of binding global climate policies has resulted in free-riding. According to many Swedish economists, the climate policy of small nations, like Sweden, should focus on increasing the likelihood of an effective global climate policy (Hassler et al., 2020).

Mitigating climate impacts is urgent given that climate change is considered to be the biggest threat modern humans have ever faced, threatening the current balance of living and affecting the quality of life (UN-HABITAT, 2022). Globally, millions of people in urban areas have experienced and are likely to face longer periods of extreme heat and cold, with more droughts and forest fires, as well as heavy rainfalls, rising sea levels, inland floods, and more severe storms. Many of these issues are also relevant to Sweden (Ministry of the Environment, 2022). The frequency and impacts of extreme weather events vary across geographical locations. For instance, the extreme summer heat of 2018 led to widespread forest fires across the country but droughts only in southern Sweden.

Climate incidents like heavy rainfalls, storms, and floods can damage urban infrastructure, sewer systems, and residential properties (Ministry of the Environment, 2022). In response, residents may avoid high-risk areas, invest in home improvements to reduce risks, and purchase home insurance for financial protection. The rising frequency of extreme weather events has led to substantial insurance claims in Sweden. Figure 4 plots the patterns of claim payments associated with storms and floods for all Swedish insurance companies from 1985 to 2022. The 2005 storm Gudrun and the 2021 Gävle flood resulted in the highest payments.[1]

On a general level, it is important to understand how climate change affects human life and behaviours to effectively design policies that mitigate the unevenly distributed adverse consequences of climate change across individuals and locations. As an example, as the flood risk increases, some areas are more affected and become less attractive. Insurance companies may raise insurance premiums, apply differential coverage rates across areas, and even discontinue coverage in certain areas, potentially affecting housing prices and aggravating inequalities. Given the data availability on floods and the housing market in Sweden, this exploration may represent a productive avenue for future research.

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[1] The largest payments related to natural events are associated with the 2005 storm Gudrun, resulting in total claims of 3.76 billion SEK. In 2021, flood-damage-related insurance compensation to households and firms amounted to 2.26 billion SEK, mainly attributed to the Gävle flood.

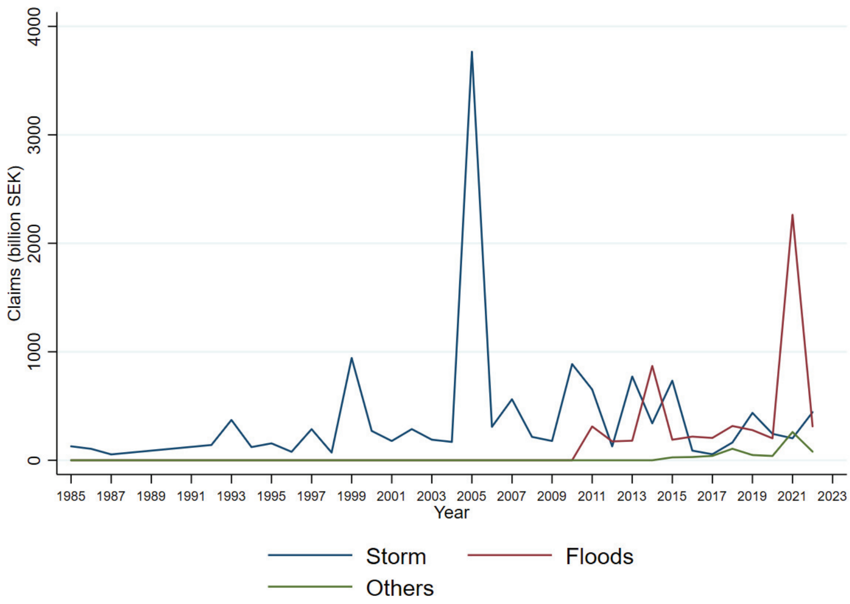


Figure 4. Approved insurance claims due to natural incidents in Sweden

Note: The data are sourced from Svensk Försäkring and represent claim payments for different types of property insurance, including basic home insurance, detached house insurance, vacation home insurance, and insurance for company properties. The claims from floods include all payments due to housing damage caused by water associated with natural and weather events.

The pronounced impacts of natural disasters in densely populated areas can potentially alter public awareness about and attitudes toward climate change, ultimately influencing public support for climate and environmental policies. As an increasing fraction of the population experience the negative impacts of climate change, their concerns and responses will shape the policy landscape. It is important to understand the determinants of environmental attitudes as public support for climate and environmental policies relies on those attitudes. Additionally, politicians' environmental concerns could potentially affect the types of policies implemented (Gagliarducci et al, 2019). For example, elected politicians could pass bills promoting environmental regulation, and urban governors could implement environmental policies aiming at decarbonizing the transport system.

Previous literature highlights that motivated beliefs and information avoidance contribute to belief polarization (Bénabou and Tirole, 2016). To avoid confirmation bias, people tend to cling to their beliefs and selectively interpret information that aligns with their existing beliefs, while disregarding contradicting evidence. Investigating the underlying factors driving diverged beliefs is crucial for understanding belief polarization. Political preferences often play a central role in this polarization, as individuals aligned with parties with heterogeneous ideologies tend to exhibit greater divergence in their views on various societal issues. Additionally, overconfidence has been identified as an important predictor of ideological extremeness (Ortoleva and Snowberg, 2015). The influence of media, the internet, and social media could further reinforce belief polarization and amplify ideological divides (Allcott et al., 2020).

The third chapter of this thesis investigates how individuals update their environmental and climate change beliefs in response to extreme weather events. Using the extensive Swedish forest fires in 2018 as a natural experiment, the study finds that individuals with stronger pre-existing beliefs about climate change and the environment escalate their concerns more than those with weaker prior beliefs. Additionally, those with stronger prior beliefs are more likely to support left-leaning parties, while those with weaker prior concerns tend to support right-leaning parties. The growing disparity suggests that information chocks affect belief polarization through motivated reasoning in the context of climate change. However, the escalated concerns do not translate into increased support for a higher carbon tax.

From a policy perspective, my research indicates that mobilizing support for effective climate policies will prove challenging. As the climate change impacts intensify and affect wider segments of the population, the likelihood of witnessing a widespread shift in attitudes toward environmental consciousness and a unified endorsement of climate policies remains low. Instead, social tensions are likely to escalate, and even positive shifts in environmental attitudes may not be adequate to bolster support for climate policies. Future research should focus on enhancing our understanding of the varying roles of different factors in shaping support for climate policies, as well as devising strategies to craft effective climate policies that can garner broad public backing.

## 2.3 Energy transition

The transition to a low-carbon society requires shifting energy supply away from coal and fossil fuels to clean energy sources. With a large share of renewable energy and nearly decarbonized electricity and heat systems, Sweden's energy system today is very "clean", relative to the rest of the world (Thalberg et al., 2022). However, this was not always the case. In 1970, the energy mix in Sweden looked very different, with 77% of energy sourced from oil, 10% from biofuels, and 10% from hydropower.[2] The oil crisis of the 1970s halted the increasing use of oil and triggered a transformation in the composition of the Swedish energy mix. This shift was not only driven by escalating oil prices but also by government policies favouring hydropower and nuclear power (Wickman, 1988; Hassler et al., 2020).

Figure 5 illustrates the evolution of Sweden's energy supply by source from 1970 to 2022. Following the energy crisis in the 1970s, the energy supply from oil decreased dramatically from 77% to 30%, and the supply from fossil fuels halved within two decades. Concurrently, nuclear power was rapidly expanded to comprise around 36% of the energy mix by 1990. Additionally, other renewable sources like hydropower, biomass, wind, and solar power increased from 19% to 24%.

The change in the composition of energy sources, induced by both external chocks and Swedish energy policies, has played a crucial role in improving air quality and reducing greenhouse gases. Industrial and residential use of oil tends to create many air pollutants, and hydropower and nuclear power are much cleaner energy sources in comparison. The oil crisis in the 1970s marked the beginning of the decline in airborne pollutants and greenhouse gas emissions (see Figures 1–3). These facts have been pointed out in previous research (Bergquist and Söderholm, 2015; Kander and Lindmark, 2004).

[2] Numbers are calculated based on energy supply data sourced from the Swedish Energy Agency. They are also used to plot Figure 5.

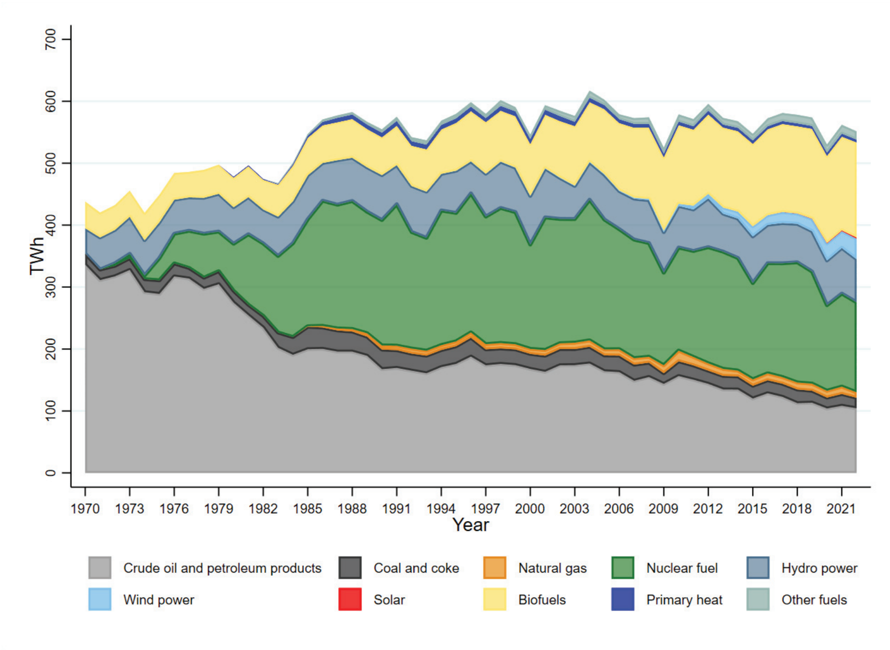


Figure 5. Energy supply by energy source in Sweden.

Note: The data on the amount of energy supplied to the Swedish energy system from various resources are from the Swedish Energy Agency and Statistics Sweden (SCB). Primary heat refers to heat pumps in district heating.

The early shifts in the energy system were not primarily motivated by environmental concerns. However, since the 1990s, climate concerns have begun to play a central role in shaping Swedish energy policies. Subsequently, Sweden has gradually reformed its energy taxes, imposed carbon taxes, increased the share of clean energy sources, and promoted renewable energy. Today, energy policies are an essential part of Swedish climate policies. Multiple interventions specifically facilitate the development and adoption of renewable energy. These policy instruments include the tradable green certificate system,[3] subsidies and tax benefits for the production of wind and solar power, and the requirement of blending biofuel into transport fuel. As of 2022, renewable sources accounted for 47%

[3] The tradable green certificate system, implemented in May 2003, serves as a market-based support system facilitating the expansion of renewable electricity. Under this system, electricity certificates are allocated to producers for every MWh of electricity generated from renewable energy sources, including wind, solar, and sometimes hydropower. Electricity suppliers are then required to purchase these electricity certificates in relation to the volume of electricity they supply (Hassler et al., 2020).

of Sweden's energy supply, with hydropower comprising 13%, biofuels 28%, and wind and solar power 6%.

Many renewable energy sources, such as wind and solar power, are intermittent, meaning that energy supply from these sources cannot be planned. As Sweden transitions towards climate neutrality, the growing reliance on these intermittent energy sources in the electricity system will lead to significant variations in electricity supply and prices, posing challenges to the electricity market. To accommodate such variability, an electricity system with highly flexible generation capacity and price-driven flexible demand is essential (Joskow, 2019).

Sweden's electricity markets consist of the day-ahead, intraday, and balancing markets. While most of the produced electricity is sold on the day-ahead market, the intraday and balancing markets adjust for demand and supply imbalances (Holmberg and Tangerås, 2023). Since it is cheaper to trade generation imbalances in the intraday market than in the balancing markets, the intraday market is expected to expand with the increasing share of wind and solar power. Although the intraday market reduces integration costs for intermittent power producers, it often lacks liquidity (Weber, 2010).

The third chapter of this thesis evaluates the performance of the Swedish intraday market and its ability to handle the increasing presence of intermittent renewable energy sources in the country's electricity system. Currently, our analysis indicates that the intraday market operates effectively. However, as the proportion of intermittent electricity sources grows significantly, the conclusions drawn may require re-evaluation. A comprehensive perspective that considers the complexity of the energy system is crucial. Furthermore, when devising strategies for integrating new energy sources on a national scale, it is important to consider the heightened integration of the Swedish energy market with the broader European market.

In addition to supply-side interventions such as those we see in the energy market, policies targeting the demand side provide another group of instruments that might be effective for achieving environmental sustainability. Often such policies encourage resource conservation which is not only relevant for energy transition but also for other environmental issues.

Urban areas drive much of the world's demand for resources, and they are major contributors to climate change, responsible for 70 percent of greenhouse gas emissions from global energy use (UN-HABITAT, 2022). In

Sweden, as of 2019, residences and cars accounted for 62% of total energy consumption (Swedish Energy Agency, 2020),[4] with approximately 56.4% of total carbon dioxide emissions associated with residential activities (Statistics Sweden, 2023).[5] In response, the Swedish government has implemented various policies to decarbonize urban transportation and promote energy efficiency in urban areas.[6]

In densely populated urban areas in Sweden, there are almost no monetary incentives for reducing residential energy and water use since there are no or low marginal costs of consumption. In most Swedish apartment buildings, electricity, heat, and water consumption are typically monitored at the building level, with costs included in the rent. Tenants in a building often split the bill based on their apartment size and thus pay a fixed monthly fee for unlimited consumption. A potential solution involves installing meters at the apartment level and charging tenants individually for their energy use. Studies show that individual billing significantly reduces electricity consumption by 25% in Sweden (Elinder et al., 2017), and total residential energy use by 25% in the U.S. (Brewer, 2022).

The fourth paper of the thesis investigates the effects of introducing a marginal price through initiating individual billing on residential hot water consumption in Swedish multi-family buildings. The findings indicate an 18% reduction in hot water usage. We also show that one SEK investment in individual billing yields energy savings equivalent to 1.56 SEK, mitigates $CO_2$ emissions by 0.62 kg (based on the international energy mix), corresponding to a social value of 1.02 SEK (using a social cost of carbon of 190 USD per ton of $CO_2$), and decreases deadweight loss by 1.17 SEK.

One could argue that emissions from residential energy use might have been addressed by the EU Emission Trading System (EU ETS) and the Swedish carbon taxes. Still, the efficiency gains of setting correct marginal prices remain, and the effects of individual billing interventions on energy conservation are of interest to countries outside the EU. Moreover, certain

[4] The residential and service sectors account for 40% of total energy use and domestic transport accounts for 22% of total use.

[5] These emissions include emissions from electricity, gas and hot water supply, water distribution, transport, services, and households.

[6] These efforts include investing in public transport and cycling infrastructure, implementing a bonus and malus system to incentivize the purchase of clean cars while imposing taxes on brown cars, mandating the blending of biofuels with transport fuels, exempting biofuels from energy and carbon taxes, investing in public fast-charging infrastructure, imposing congestion charges in Stockholm and Gothenburg, and improving energy efficiency in new and existing buildings (Swedish Environmental Protection Agency, 2023).

sectors, such as energy production from biofuels, are exempted from EU ETS. To reduce emissions from those sectors, Sweden adopted the EU's Effort Sharing Regulation (ESR) in 2018. This regulation targets emission reduction from road transport, heating of buildings, agriculture, small industrial installations, and waste management. The rollout of individual billing for energy use aligns with the mitigation objectives outlined in the ESR, contributing to Sweden's broader efforts to mitigate climate change.

One should also not forget the water that can be saved with the introduction of individual billing. While Sweden is a developed country with ample fresh water sources, climate-change-induced events such as the hot and dry summer of 2018 forced municipalities to enact conservation policies like irrigation prohibition and information campaigns. The fact that many consumers do not face the full marginal cost of consumption contributed to the shortages.

On a more general level, information provision to consumers and non-pecuniary incentives are two other demand-side strategies encouraging resource conservation. In the case of water conservation, studies show that greater consumption information could lower consumption, potentially by fostering cost awareness (e.g., Daminato et al., 2021). On the other hand, other studies find no effects or increased consumption (e.g., Wichman, 2017), possibly because consumers are rationally inattentive to the water bill since it only accounts for a small fraction of their expenditures or because paying a price could alleviate the moral guilt of overconsumption (Gneezy and Rustichini, 2000). When it comes to non-pecuniary incentives, several studies show that social comparisons are more effective than appealing to people's pro-social preferences and can reduce residential consumption by up to 7% in the short run, with some effects lasting for years (e.g., Torres and Carlsson, 2018).

Compared to the effects of non-pecuniary incentives and providing information, the 18% effect of volumetric pricing that we find in our study is of an order of magnitude higher. Among policy instruments (Stavins, 2011), our results suggest that those creating price incentives have very attractive features for promoting resource conservation. We believe our paper provides an important lesson for demand-side environmental policies in general.

## 2.4 Residential segregation

Cities play a crucial role in driving economic growth. However, alongside environmental concerns, urban expansion has also brought about social challenges. A significant portion of these issues arises from the unequal distribution of economic advancements. Similar to environmental sustainability, social sustainability, which involves fostering the harmonious coexistence of diverse societal groups and promoting social inclusion, is now recognized as a vital factor in determining quality of life. Furthermore, both environmental and social inequalities often exhibit notable spatial patterns, such as variations in residential socio-economic status across different areas (Verhoef and Nijkamp, 2004).

An increase in income inequality, particularly due to a surge in top incomes, has been documented in many industrialized countries since World War II (Atkinson et al., 2011). Previous literature shows that higher levels of income inequality are associated with lower rates of social mobility (Kearney and Levine, 2016). With urbanisation, low-income people migrate from rural to urban areas in search of better job opportunities. However, due to the higher cost of living in cities, they often end up concentrated in impoverished neighbourhoods (Massey, 1996). The systematic differences in the neighbourhood choices made by households with varying income levels are referred to as residential segregation by income.

Residential segregation is associated with large societal costs; for example, insecure housing and social exclusion have negative effects on educational attainment, income, and health (Ludwig et al., 2012; Ridley et al., 2020), which, in turn, may contribute to the poverty trap (De Quidt and Haushofer, 2016). Growing up in poor neighbourhoods has adverse effects on children's development and future social outcomes (Chetty and Hendren, 2018), thereby reducing income mobility and reproducing existing inequalities. There is causal evidence such as studies demonstrating the beneficial effects of relocating from low-income neighbourhoods (Katz et al., 2001; Chetty et al., 2016). Moreover, empirical studies have linked distrust and violent crime to the spatial separation of people, possibly because segregation results in a lack of social cohesion, due to fewer opportunities for social interactions across population groups (Kelly, 2000; Gustavsson and Jordahl, 2008).

Understanding the underlying drivers of segregation is crucial for mitigating its adverse impacts. During the past few decades, income segregation has intensified within metropolitan areas in the U.S. (Watson, 2009). A common feature across these places is that neighbourhoods in the suburban areas tend to have higher levels of income compared to the central areas. Economists have shown that household preferences regarding commuting time, access to public transit, local public services, physical amenities, and the social characteristics of their neighbours contribute to segregation (Rosenthal and Ross, 2015). Notably, racial and ethnic segregation remains a prominent feature of many cities in the U.S., and studies have shown that the difference between African Americans and the white population is beyond what differences in incomes and demographic characteristics can explain (Bayer et al., 2004).

In Sweden, residential income segregation is also rising, along with income inequality. Between 1990 and 2017, pre-tax income segregation increased by 62%, and disposable income segregation increased by 37% (Hu and Liang, 2022). Since the 1990s, the Swedish government has implemented numerous place-based interventions to combat segregation, including “Blommansatningen”, “Storstadssatsningen”, LUA, URBAN-15, and the recent vulnerable areas initiative. These policies aim at improving employment opportunities, housing conditions, and school results, as well as preventing crime. Yet, assessing the effects of different measures is challenging since several measures typically have been carried out at the same time (Andersson et al., 2023).

Despite policy efforts, there is limited empirical evidence and knowledge on the most effective approaches to address segregation issues. It remains unclear whether place-based interventions or policies targeting disadvantaged groups more generally are more effective, as well as whether segregation prevention or mitigation of its consequences yields better results. Given that income segregation is closely linked to income inequality, it has been suggested that income redistribution from rich to poor households could help prevent their concentration in different neighbourhoods. Several recent studies document a positive relationship between income inequality and residential segregation (Reardon and Bischoff, 2011). However, without causal evidence linking income inequality to segregation, this association provides insufficient guidance to policymakers.

The final paper of the thesis uses Swedish full-population panel data to estimate the causal effects of inequality on segregation, and the findings are that reducing pre-tax income inequality has positive effects, whereas income redistribution equalizing disposable incomes has no effects on residential sorting. Our findings support Schelling's (1969) hypothesis that preferences for similar neighbours, such as those with similar abilities to earn income, are a major determinant of residential choices. In other words, people avoid others that are too different from themselves, and thus, decreasing ability and earnings differences will lead to neighbourhoods with a better mix of residents from different parts of the income distribution. These findings suggest that attention and resources should be directed toward education and labour market policies.

From a broader perspective, while economics has long focused on studying inequality among population groups, urban and public economists have only recently turned their attention to the spatial aspects of inequality. Our understanding of the causes and effects of spatial inequality remains incomplete, constraining the capacity of research to offer practical policy suggestions. However, with the increasing availability of extensive registry data spanning long periods and spatially coded data on various amenities such as public and private services, physical infrastructure, and natural environment, I anticipate significant research advancements in the coming decade.

# 3. Summary of papers

## 3.1 Paper 1: Toxic metal injustice? Socioeconomic status at birth and exposure to airborne pollution

Despite efforts to reduce emissions and improve air quality, pollution is still present and unequally distributed geographically (Shapiro and Walker 2021). This disparity in distribution may lead to disproportionate exposure among the poor and the rich, potentially exacerbating existing socioeconomic inequalities and influencing children's life chances. Early-life exposure to pollution has long-term implications for human capital development.

A recent study by Currie et al. (2023) uses fine-grained data on ambient particulate matter (PM 2.5) in the U.S., revealing a significant reduction in the racial gap in exposure over recent decades, largely attributed to more stringent environmental policy. Yet, limited evidence exists regarding environmental disparities based on ambient air pollution for other countries and with respect to other pollutants.

This paper investigates whether there exists socioeconomic inequality in exposure to air pollution of toxic metals across Sweden. We compile a comprehensive dataset of the Swedish population born between 1990 and 2020, including information on parents' socioeconomic status, mothers' pregnancy details, residential locations, exposure to various air pollution, and proximity to pollution sources at birth. The data is captured at a grid-level, with grids measuring 250×250 meters for urban areas and 1000×1000 meters for rural areas. The primary objective is to trace the spatial distributions of airborne arsenic, lead, and mercury in Sweden and examine the spatial correlation between exposure to these pollutants and socioeconomic status (SES) among the population of newborn children.

Our contributions to the literature are threefold. Firstly, we focus on exposure to toxic airborne metal pollution – arsenic, lead, and mercury – which impacts individuals' cognitive function and various socioeconomic outcomes later in life (Grönqvist et al., 2020). Previous toxicological studies have focused on the health consequences of exposure to toxic metals through food and water (Fowler et al. 2022), but little is known about the effects of exposure to airborne toxic metals.

Secondly, we investigate the pollution exposure among newborn children for several cohorts over time. This relates to the literature on neighbourhood effects on children's development, suggesting that parents actively select high-quality neighbourhoods for their children (Chetty and Hendren, 2018; Heckman and Landersø, 2022). However, limited evidence exists on whether parents select neighbourhoods with better physical environments to avoid air pollution.

Thirdly, we use data on all moving events during pregnancies to explore whether sorting at birth masks geographical sorting that took place before the children were born. Our paper therefore connects to the literature on pollution distribution, its long-term consequences for geographical sorting, and the role of information (e.g. Kuminoff et al., 2013).

Our main finding is that children with different SES at birth are evenly distributed across Sweden with regard to exposure to airborne pollution of arsenic, lead, and mercury over three decades. We do observe a weak spatial association between SES and toxic metal exposure in major cities. Our results suggest that pollution exposure does not exacerbate existing socioeconomic inequalities at birth. Additionally, we find no sorting between high- and low-SES families in relocation during the period surrounding conception.

These results raise the question of whether parents are aware of pollution exposure. To explore this, we examine the spatial correlation between SES and more salient pollutants like PM10 and families' distance to visible pollution sources like industrial plants. Weak correlations between SES and PM10 exposure and proximity to industrial plants suggest that parents do not consider these issues serious enough to relocate.

## 3.2 Paper 2: Who is concerned about climate change when forests are burning? Evidence from Swedish forest fires

This paper examines how individuals update their environmental attitudes in response to extreme climate events. Despite the urgent need for climate action, global climate policy remains scarce, primarily due to a lack of public support. Research highlights the crucial role of climate change beliefs in generating public support for policies mitigating climate change impacts and reducing pollution. Climate events have the potential to raise awareness of climate change and other environmental hazards. While previous studies in environmental psychology, political science, and economics highlight the link between personal exposure to such events and pro-environmental attitudes, only a few papers provide causal evidence.

To answer this question with stronger causal claims, I use the extensive Swedish forest fires in 2018 as a natural experiment, combining environmental opinion survey data with a municipal panel of forest fire damages, temperatures, and precipitation, and respondents' exposure to climate change news. Salience and motivated reasoning could shape our environmental beliefs in response to fires.

As the severity of the 2018 fires varied substantially across different regions, to investigate the role of salience, I explore whether the impacts of the fires on environmental attitudes depend on residents' exposure to local fires. Additionally, to explore the role of motivated reasoning, I examine how the effects of fires vary among individuals supporting parties with different preexisting environmental attitudes. Political polarization in environmental attitudes has been well documented, and political scientists attribute it to motivated reasoning, where individuals update beliefs in a way that aligns with their prior beliefs. However, it remains empirically unclear whether the growing prominence of climate events could potentially widen or bridge these political divides in attitudes.

My results show a surge in environmental concerns following the fires. The extent of these increases was weakly influenced by the intensity of local fires but strongly affected by individuals' prior beliefs. Left-leaning individuals, with stronger preexisting concerns, experienced a significant escalation in their degree of concerns relative to right-leaning individuals. The growing disparity suggests that climate events exacerbate political polarization in environmental attitudes rather than mitigate it. Additionally, exposure to climate change news does not appear to contribute to the political polarization of concerns, strengthening the interpretation that motivated reasoning along partisan lines shapes differential reactions to climate disasters. I find no evidence of effects on support for a higher carbon tax.

This study contributes to the emerging literature studying how extreme events affect public support for parties promoting environmental regulations. It has important implications. Due to motivated reasoning, information campaigns aimed at providing better and more information about climate change may not be sufficient to broadly shift public opinions. Furthermore, concerns about climate change and the environment may not necessarily translate into support for specific environmental and climate policies.

## 3.3 Paper 3: The effects of wind power on electricity markets: A case study of the Swedish intraday market

As the Swedish electricity system is rapidly transitioning towards net zero emissions, renewable energy sources, such as wind and solar power, will expand significantly. One common feature of wind and solar power is that energy supply from these sources cannot be planned. The intermittent nature of these energy sources presents challenges for the electricity system, increasing variation in supply and prices. To accommodate such variability, an electricity system with highly flexible generation capacity and price-driven flexible demand is needed (Joskow, 2019). In this context, the electricity intraday market plays a crucial role, potentially reducing integration costs for intermittent power and benefiting wind and solar power producers.

The intraday market is likely to expand with incremental shares of intermittent renewable power generation. Theoretical research suggests that the intraday market provides positive premia to reward flexible generators for their contribution to power system security (Soysal et al., 2017). Wind power producers prefer to trade their generation imbalances in the intraday market than at a higher cost in balancing markets. As electricity generated by wind power increases in the system, there is an increasing demand for ramping capacity at congested hours, which will be reflected by a positive price premium in the intraday market. Yet, evidence suggests that many

European markets, including the Swedish one, lack liquidity, potentially leading to inefficiency and higher imbalance costs (Weber, 2010).

This paper investigates the performance and functioning of the Swedish intraday market and aims to understand whether this market expectedly rewards its participants. Using Karanfil and Li's (2017) approach, we examine whether intraday price premia reflects market fundamentals, indicating the market's effectiveness in integrating imbalances caused by intermittent generation.

Our study focuses on Sweden due to its significant wind power growth and diverse generation mix, making it a valuable case to study and providing implications for countries transitioning to significant shares of wind power. We also study unplanned nuclear power outages, which could create significant imbalances when adopting more wind power. In our analysis, we account for other market fundamentals such as cross-region flows.

We find that, in areas with high electricity consumption and large wind power share, intraday price premia mostly respond to wind power forecast errors, as they should if the intraday market is efficient. However, we find no effect of unplanned nuclear power plant outages on intraday price premia. Overall, our results suggest that the Swedish intraday market is functioning properly, and it rewards flexibility in the expected way by sending correct price signals to flexibility providers.

## 3.4 Paper 4: Mind the tap – how volumetric pricing affects residential hot water consumption

Water is an increasingly scarce resource. Factors such as population growth, urbanisation, pollution, and climate change worsen water scarcity, with half of the world's population projected to live in water-stressed areas by 2025. In urban areas, water is often provided for free or at a price below the long-run marginal cost of supply (Olmstead and Stavins, 2009). For instance, in multi-family buildings, water consumption is typically monitored at the building level, rather than at the apartment level, and for that reason, unlimited consumption of both hot and cold water is often included in the rent. Economic theory predicts that tenants not facing the full marginal cost of consumption will use more water than collectively optimal.

The traditional economic remedy advocates for setting prices correctly (Ornaghi and Tonin, 2021). However, studies on water conservation have predominantly emphasized two alternative types of interventions. The first involves providing consumers with information regarding prices and consumption levels. The second entails non-pecuniary incentives, such as appealing to pro-social inclinations or social comparisons.

This paper focuses on the impacts of price incentives on water conservation. With individual metering and billing (IMB), consumption can be monitored at the apartment level, allowing volumetric pricing where each household pays its water bill and thus is charged a marginal cost reflecting the market price. Using high-frequency data for several hundred apartments in the municipality of Kumla in Sweden from 2012-2016, we investigate the effects of introducing individual billing on hot water use. Meters were installed and consumption was reported to the tenants for at least two and sometimes up to 16 months before apartment-level billing began. This allows us to follow consumption before and after volumetric pricing was imposed. Additionally, individual billing was introduced on different dates across the apartments, enabling us to apply a quasi-experimental design. We conduct various panel estimations, using before-after, difference-in-differences, and event-study methods.

Our findings show that individual billing results in an 18% reduction in hot water usage. Although the estimated effects are smaller in the summer, they were fairly homogeneous across different days of the week, consumption quartiles, and apartments with varying characteristics, and evenly distributed between bathroom and kitchen usage. These results suggest that water consumption can be significantly reduced by moving from a fixed water cost to volumetric pricing.

Compared to the effects of information and non-pecuniary incentives, the 18% effect of volumetric pricing that we find is of an order of magnitude higher. Additionally, the effect of the price change is immediate and permanent, and the maintenance cost of IMB is low. Furthermore, our cost-benefit analysis indicates that IMB can cost-effectively reduce the consumption of hot water. A one SEK investment in IMB entails efficiency gains of 1.17 SEK, water saved with a market value of 2.34 SEK, and energy saved with a market value of 1.56 SEK. Moreover, the social value of avoided $CO_2$ is greater than 1 SEK in many contexts.

## 3.5 Paper 5: Does income redistribution prevent residential segregation?

Economists have mapped the rising income inequality in the industrialized world since World War II and attributed much of this trend to increasing top incomes. A broad literature suggests that inequality has negative consequences on economic, health, and social outcomes at the individual level. It is important to recognize that at the neighbourhood level, average incomes also display sharp, non-random spatial gaps, which is typically referred to as residential segregation by income.

Segregation could create some neighbourhoods with a high share of low-income residents. Researchers have found empirical evidence showing that living or growing up in such neighbourhoods has adverse effects on, e.g., college attendance and earnings (Katz et al., 2001; Chetty et al., 2016). There are only a handful of empirical studies of income inequality as a driver of residential segregation. These studies mainly documented correlations between changes in inequality and segregation, leaving policymakers with limited guidance on effective interventions for preventing segregation.

This study utilizes individual-level geo-coded administrative data covering the entire population in Sweden from 1990 to 2017 to investigate the causal effects of income inequality on income segregation. We focus on the role of determinants related to public redistribution and sociodemographic composition, offering detailed insights for policymakers seeking to combat segregation.

Traditionally, researchers have focused on two types of residential sorting: sorting by residents' willingness and abilities to pay for housing quality and public goods (Tiebout, 1956), and sorting by their preferences for neighbours of similar backgrounds, like income, education levels and culture (Schelling, 1969). From a policy perspective, understanding these determinants is crucial. Taxes and transfers affect disposable incomes given a certain level of pre-tax income and such redistribution policies could impact the first type of segregation. Policies affecting the determinants of pre-tax income such as education could change the second type of segregation.

Two challenges arise when estimating the causal effects of inequality on segregation. Firstly, existing segregation may reinforce inequality through reverse causation. Secondly, changing economic conditions affect neighbourhoods differently depending on their residential composition. This study addresses these challenges and rules out reverse causation and mechanical effects. It leverages newly arrived residents, who affect the municipal income composition but are not part of existing segregation, to identify pre-tax income inequality effects. To identify the effects of disposable income inequality, we rely on tax-system-driven municipality-by-year variation in disposable income distributions.

The findings suggest that pre-tax income inequality affects residential sorting, but not disposable income inequality. Moreover, once controlling for the educational composition of residents, the effects of pre-tax income inequality substantially decrease. This implies that redistribution policies have limited effects on segregation. On the other hand, increasing pre-tax incomes of low-income residents through educational interventions is likely effective in fighting segregation.

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# Popular science summary

After a century of remarkable economic growth, the world faces unprecedented environmental challenges, spanning from resource depletion to climate change. Rapid urbanisation exacerbates environmental problems, like air pollution, and contributes to social disparities, including marginalized neighbourhoods. The United Nations' 2030 agenda for sustainable development emphasizes environmental progress and social equity through goals like climate action, renewable energy promotion, and the reduction of inequalities.

This thesis explores the complex interplays between economics, environment, and society, particularly focusing on Swedish contexts. Employing recently available data sources and modern statistical methods, it aims to extract insights crucial for informing policy decisions.

Paper 1 assesses whether there exists a discrepancy in air pollution exposure among children from economically disadvantaged and advantaged backgrounds. Unlike in numerous other countries, our investigation reveals no discernible differences in exposure to harmful pollutants between poor and affluent areas in Sweden since the 1990s.

Paper 2 examines the effects of the 2018 Swedish forest fires on individuals' environmental concerns. The findings show that only individuals with preexisting environmental concerns experienced heightened apprehension regarding climate change in response to the fires. Additionally, the study highlights a widening gap in environmental concerns between supporters of right- and left-leaning political parties. Furthermore, the research does not indicate any noticeable rise in support for policies targeting climate change mitigation.

Paper 3 investigates the impacts of recent wind power growth in Sweden on the electricity market, a pertinent inquiry considering the growing influence of weather patterns on electricity availability. Our results offer reassurance regarding the resilience of the Swedish electricity market.

Paper 4 evaluates how the implementation of apartment-level hot water billing affects residential consumption of hot water in multi-family buildings. We find an 18% reduction in hot water usage when apartments transition from a fixed water fee included in the monthly rent to individually paying for their own consumption.

Paper 5 studies the relationship between income inequality, characterized by disparities in earnings among individuals, and residential segregation, the spatial division of people into distinct neighborhoods based on their income levels. The primary finding suggests that more income redistribution between affluent and disadvantaged individuals does not influence their decisions to reside in separate areas, consequently failing to promote socioeconomically diverse urban neighborhoods.

While my research offers glimpses of optimism, showcasing the tangible impacts of policy packages and certain targeted interventions, it also underscores the formidable challenge of gathering broad support for environmental policies.

# Populärvetenskaplig sammanfattning

Efter ett århundrade av enastående ekonomisk tillväxt står världen inför oöverträffade miljöutmaningar, som sträcker sig från resursutarmning till klimatförändringar. Snabb urbanisering förvärrar miljöproblem som luftföroreningar och bidrar till sociala klyftor, inklusive marginaliserade områden. FN:s agenda för hållbar utveckling till 2030 betonar miljöframsteg och social rättvisa genom mål som klimatåtgärder, främjande av förnybar energi och minskning av ojämlikheter.

Denna avhandling utforskar de komplexa samspelen mellan ekonomi, miljö och samhälle, med särskilt fokus på svenska sammanhang. Genom att använda nyligen tillgängliga datakällor och moderna statistiska metoder syftar den till att tillhandahålla insikter som är viktiga för informerade politiska beslut.

Uppsats 1 utforskar om det finns skillnader i hur mycket barn från resurssvaga och resursstarka familjer utsätts för luftföroreningar. Till skillnad från i många andra länder visar vår undersökning inga tydliga mönster i exponering av skadliga föroreningar mellan låg- och höginkomstområden i Sverige sedan 1990-talet.

Uppsats 2 undersöker effekterna av de svenska skogsbränderna 2018 på människors attityder till miljöfrågor. Resultaten indikerar att endast redan miljömedvetna individer upplevde ökad oro för klimatförändringar efter bränderna. Vidare belyser studien en ökande klyfta i miljöinställning mellan anhängare av olika politiska partier. Dessutom visar forskningen inte på något märkbart ökat stöd för klimatpolitik.

Uppsats 3 bedömer konsekvenserna av de senaste årens vindkraftsutbyggnad i Sverige på elmarknaden, en relevant fråga med tanke på det ökande inflytande vädret har fått på tillgängligheten av elektricitet. Våra resultat visar att elmarknaden fungerar som den bör göra.

Artikel 4 undersöker hur införandet av individuell varmvattenmätning på lägenhetsnivå påverkar hushållens konsumtion av varmvatten i flerbostadshus. Vi finner en 18% minskning av varmvattenanvändning när lägenheter övergår från en fast vattenavgift inkluderad i månadshyran till att individuellt betala för sin egen förbrukning.

Artikel 5 studerar förhållandet mellan inkomstojämlikhet, dvs. ojämlikt fördelade inkomster mellan individer, och bostadssegregation i termer av att människor med olika inkomster bor i olika grannskap. Huvudslutsatsen är att mer omfördelning från rika till fattiga människor inte påverkar deras beslut att bo segregerat i olika områden, och således inte främjar socioekonomiskt blandade grannskap.

Även om min forskning erbjuder glimtar av optimism, då den visar att både åtgärdsprogram och vissa enskilda interventioner har avsedda konsekvenser, understryker den också vilken utmaning det är att samla brett stöd för miljöpolitik.

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*Uppsala, 2024-04-26*
*Xiao*

# III

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# The effects of wind power on electricity markets: A case study of the Swedish intraday market

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A B S T R A C T

We investigate the process of electricity price formation in the Swedish intraday market, given a large share of wind power in the Swedish electricity system. According to Karanfil and Li's (2017) approach, if the intraday market is efficient, with large shares of intermittent electricity in the entire electricity system, intraday prices should send signals based on scarcity pricing for balancing power. Based on this theory, we analyze Swedish electricity market data for the period 2015–2018 and find that the Swedish intraday market, despite its small trading volumes, is functioning properly. In particular, our results show that intraday price premia mostly respond to wind power forecast errors and other imbalances resulting from either supply or demand sides of the electricity market, as they should if the intraday market is efficient. The results of wind power forecast errors hold for central and southern Sweden, but not for northern Sweden where the share of wind power production is still very small. However, we find no effect of unplanned nuclear power plant outages on intraday price premia.


## 1. Introduction

European electricity systems are currently undergoing a rapid transformation as more and more electricity is produced from intermittent renewable energy sources, such as wind and solar power. The same trend applies to the Swedish electricity system. According to the Swedish Transmission System Operator — Svenska Kraftnät (2017), electricity produced from wind power in Sweden increased from 6.2 TWh in 2011 to about 17 TWh by the end of 2017. Renewable electricity generation in Sweden has been promoted through a mix of policies for almost three decades. Some of these policies are national, some are regional, while others are established at the EU level. But only recently did the Swedish Parliament decide that by 2040, at the latest, Sweden will have a 100% renewable electricity production system. This means that renewable electricity generation in the form of bioenergy and intermittent power, primarily wind and solar power, has to be significantly expanded to replace non-intermittent energy sources such as nuclear power. The share of wind in the Swedish generation mix is expected to be more than 20% by the end of 2020 and will increase to 40% in 2050. In other words, wind power will fully replace nuclear power in a 30-year time horizon (Jaraitė et al. 2019).

Not surprisingly, these changes pose challenges for the entire Swedish electricity system: to accommodate supply variability caused by the intermittent nature of electricity generated from wind and solar, an electricity system with highly flexible generation capacity, or highly price-driven flexible demand, or both are needed (Joskow 2019). Specifically, to solve these challenges in a cost-effective way, Sweden needs to have decentralized, competitive, and well-functioning sequential electricity markets, such as day-ahead and intraday electricity markets.

In this study, we focus on the Swedish sequential electricity markets and provide some evidence for the argument that appropriately designed markets provide the incentives to cost-effectively integrate intermittent power generation. As markets provide a natural place for

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flexible resources to trade in, well-functioning markets, in principle, should offer incentives for balancing power supply and demand both in the short run and in the long run. In particular, there is a common understanding that the role of intraday markets is likely to expand with the incremental shares of intermittent renewable power generation. Well-functioning intraday markets may well lower societal costs of intermittent power integration and may directly benefit, for example, wind power producers who otherwise have to use other balancing strategies or to trade their generation imbalances at a higher cost in balancing markets. The theoretically implied positive premia (Soysal et al. 2017) in the intraday market should also adequately reward flexible generators for their timely contribution to power system security, thus making it profitable for them to stay in this market. More specifically, as the time approaches the delivery hourly, the market price of electricity should include a premium because of the loss of flexibility. As electricity generated by wind power increases in the system, there is an increasing demand for ramping capacity at congested hours, which will be reflected by a positive price premium in the intraday market. Therefore, the differences between electricity prices in the intraday and day-ahead markets can be considered to be an intraday price premium.

Yet, there is a lot of evidence showing that many European intraday markets, including the Swedish intraday market, are illiquid and hence might be inefficient and result in higher costs of imbalances (Weber 2010). Historically, the volume of trade on the Swedish intraday market has been relatively low, especially compared to that in the day-ahead market. The low liquidity in the Swedish intraday market has led to concerns that many potential market participants may have been discouraged from participating in this market. According to the Swedish Energy Markets Inspectorate (2017), currently, the intraday market is used primarily by balance responsible parties, which are mainly big power producing companies, although there is no requirement for the intraday market participant to be a balance responsible party.

This paper aims to further investigate the performance and functioning of the Swedish intraday market and to understand whether this market expectedly rewards its participants. To understand this, we will look at price formation in the intraday market and its relation to price formation in the day-ahead market, and we will analyze whether intraday price premia – calculated as differences between intraday electricity prices and day-ahead electricity prices – are responding to market fundamentals, namely imbalances caused by wind power and other power-generating technologies, as well as the interconnection system. Following Karanfil and Li's (2017) approach, if causality between intraday price premia and market fundamentals can be established, it is reasonable to conclude that the intraday market is effective and, hence, capable of integrating increasing imbalances caused by intermittent electricity generation. In other words, a well-functioning intraday market should reward flexibility in the expected way by sending correct price signals to flexibility providers.

To date, besides us, only the concurrent paper by Spodniak et al. (2020) have applied Karanfil and Li's novel approach to investigate the functioning of modern intraday markets. Our paper provides important new policy insights compared to the other two papers. First, the recent rapid growth in wind power generation makes the Swedish intraday market, which functions alongside quite diverse power generation mixes, an interesting case to study as it has not been profoundly explored. Unlike Karanfil and Li (2017), we investigate four Swedish electricity price zones with different energy generation mix, while they focus on the Danish market with two electricity price zones with similar energy mix.

Second, the rise of wind power (as a share of total generation) from low levels is more recent in Sweden than in Denmark (Karanfil and Li (2017). The share of wind power has increased from 4.6% to 10.4% in Sweden from 2011 to 2017, while it is more stable around and above 30% since 2011 in Denmark. Our study is of great interest for countries with low wind power shares transitioning or considering to transition to a system with significant shares of wind power.

Third, our paper is important for understanding the interaction between wind power and nuclear power as nuclear power is common in many countries, although not in Denmark. Among other things, we study unplanned nuclear power outages, which could create significant imbalances to consider when adopting more wind power. To the best of our knowledge, this has not been done before. This analysis, therefore, may provide some early insights to policy makers, scholars, and practitioners on how gradual nuclear power phase-outs together with increasing intermittent power generation — a situation that is and will be relevant to some European countries — may affect electricity markets.

Finally, compared to the study by Spodniak et al. (2020) on the Nordic electricity markets (including the Swedish one), our paper considers additional important major market fundamentals needed for better understanding the functioning of electricity markets. They do not address fundamentals such as cross-region flows and imbalances related to nuclear power.

Our key findings can be summarized as follows. Wind power forecast errors are estimated to have the negative effect on intraday price premia in central and southern Sweden, but no effect in the north of the country potentially due to smaller wind penetration in this region than in the remaining regions. However, we find no evidence of unplanned nuclear plant outages having effects on intraday price premia in central Sweden — SE3 electricity price area. These outages, however, are estimated to be positively associated with cross-region flows in SE3 area. Electricity price area SE3 has the least transmission constraints compared with the other electricity price areas in Sweden. Hence, we suspect that when there are forced outages in nuclear power plants, producers or consumers are likely to absorb these shocks by buying electricity from the five adjacent electricity price areas instead.[1] Therefore, intraday price premia can be unaffected by these imbalances.

The paper proceeds as follows. Section 2 provides a brief literature review. Section 3 gives a short overview of the structure of the Swedish electricity markets and discusses data used in this study. Section 4 describes the model specifications and estimation methods. Section 5 reports the results from both baseline and robustness empirical models. Section 6 concludes.

## 2. Literature review

According to Joskow (2019), next to various flexible demand-inducing strategies, decentralized and competitive sequential electricity markets are commonly used to reduce the market inefficiency caused by intermittent renewable energy. Our paper relates to studies in energy economics assessing the importance of intraday markets in accommodating growing shares of intermittent renewable energy in electricity systems.

As shares of intermittent renewable electricity have become substantial, more market players are expected to participate in the intraday market. Scharff and Amelin (2016) point out that there are several reasons why this market is attractive for market participants. First, it offers a possibility to reduce the imbalance costs to which electricity consumers/producers are exposed to when supplying/consuming more or less electricity than they planned. Based on simulation studies, Mauritzen (2015) provides some evidence showing that the option of trading in the intraday market can reduce balancing costs related to a large share of wind power in the system. This will directly benefit wind power producers who otherwise have to use other balancing strategies or trade their generation imbalances at a higher cost in balancing markets (Borggrefe and Neuhoff 2011). Second, the intraday

[1] Stockholm (SE3) is connected with Sundsvall (SE2), Malmö (SE4), Norway East (NO1), Denmark West (DK1) and Finland (FI).

**Table 1**
Summary statistics from January 2015 to June 2018.

| | Mean | S·D | Median | Max | Min | Skewness | Kurtosis | Units |
|---|---|---|---|---|---|---|---|---|
| **SE1** | | | | | | | | |
| Intraday price premia | −0.460 | 4.111 | 0 | 134.6 | −105.1 | 5.651 | 307.4 | EUR/MWh |
| Wind forecast errors | −0.890 | 36.49 | −2 | 299 | −236 | −0.202 | 7.881 | MWh |
| Non-wind forecast errors | −18.45 | 139.5 | 0 | 1540 | −902 | −0.735 | 7.735 | MWh |
| Load forecast errors | −4.361 | 84.09 | −5 | 1604 | −476 | 0.286 | 9.013 | MWh |
| Intraday flows | 0.344 | 97.86 | 0 | 980 | −913.1 | 0.0547 | 19.82 | MWh |
| Congestion | 6150 | 971.6 | 6223 | 8175 | 0 | −0.422 | 3.559 | MW |
| **SE2** | | | | | | | | |
| Intraday price premia | −0.938 | 4.109 | −0.560 | 62.64 | −130.0 | −4.120 | 128.3 | EUR/MWh |
| Wind forecast errors | 1.217 | 110.1 | −3 | 681 | −817 | −0.478 | 7.522 | MWh |
| Non-wind forecast errors | −10.18 | 198.6 | 1 | 1358 | −1105 | −0.286 | 4.690 | MWh |
| Load forecast errors | −49.20 | 154.1 | −45 | 1508 | −1010 | 0.201 | 5.369 | MWh |
| Intraday flows | −1.945 | 101.8 | 0 | 718.7 | −1153 | −0.233 | 12.08 | MWh |
| Congestion | 14,115 | 1485 | 14,361 | 17,070 | 0 | −2.214 | 17.51 | MW |
| **SE3** | | | | | | | | |
| Intraday price premia | −0.954 | 4.587 | −0.660 | 167.3 | −137.6 | 2.113 | 165.4 | EUR/MWh |
| Wind forecast errors | −6.411 | 120.1 | −8 | 541 | −1067 | −1.039 | 10.02 | MWh |
| Non-wind forecast errors | 51.48 | 169.2 | 32 | 1121 | −728 | 0.564 | 4.535 | MWh |
| Load forecast errors | −25.70 | 317.3 | −31 | 1725 | −1840 | 0.116 | 3.603 | MWh |
| Intraday flows | 5.592 | 168.5 | 0.3 | 1349 | −1431 | 1.246 | 16.21 | MWh |
| Congestion | 11,464 | 1799 | 11,550 | 16,920 | 0 | −0.479 | 4.287 | MW |
| Forced outages | 1.749 | 12.44 | 0 | 737.3 | 0 | 26.58 | 1011 | MWh |
| **SE4** | | | | | | | | |
| Intraday price premia | −0.147 | 4.350 | 0 | 177.4 | −133.5 | 3.783 | 375.3 | EUR/MWh |
| Wind forecast errors | 11.18 | 77.91 | 6 | 530 | −571 | 0.0943 | 5.194 | MWh |
| Non-wind forecast errors | 8.434 | 92.07 | 9 | 1929 | −485 | 2.175 | 43.81 | MWh |
| Load forecast errors | −17.17 | 144.2 | −14 | 924 | −1007 | −0.475 | 6.211 | MWh |
| Intraday flows | 5.109 | 77.80 | 0 | 1104 | −1430 | −0.0803 | 37.80 | MWh |
| Congestion | 3523 | 1125 | 3545 | 6787 | 0 | −0.341 | 2.986 | MW |

*Notes:* Forced outages of nuclear power plants measure the unavailable capacity of the nuclear plants per hour, which is only available in SE3. The reason is that all Swedish nuclear power plants are located in SE3.

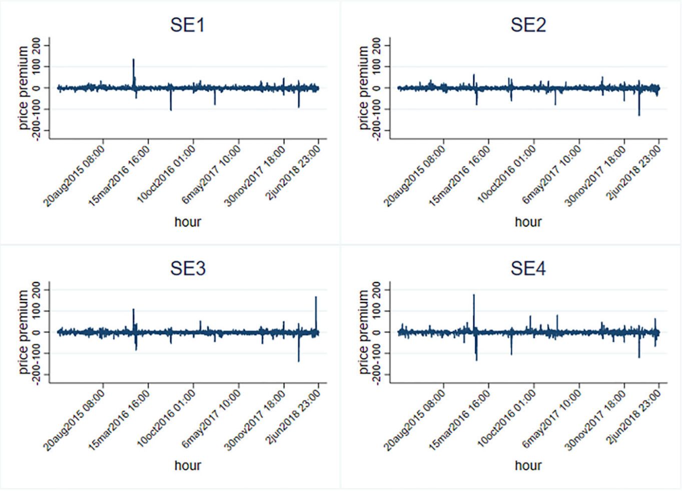


**Fig. 1.** The hourly intraday price premia for each bidding area from 2015 to 2018 in Sweden. *Notes:* Intraday price premia are measured in EUR/MWh. They are adjusted to zero at the hours when there are no trades performed in the intraday market because price premia can no longer send price signals about the scarcity of electricity when there is no trade taking place in the intraday market.

market provides a possibility for participants to optimize own production/consumption schedules, for example, by buying electricity to reduce generation in their own power plant that would be costlier to run. Last but not the least, intraday trading can also be used as a venue to sell flexibility of own production/consumption to other market participants who need this flexibility and are willing to pay for it.

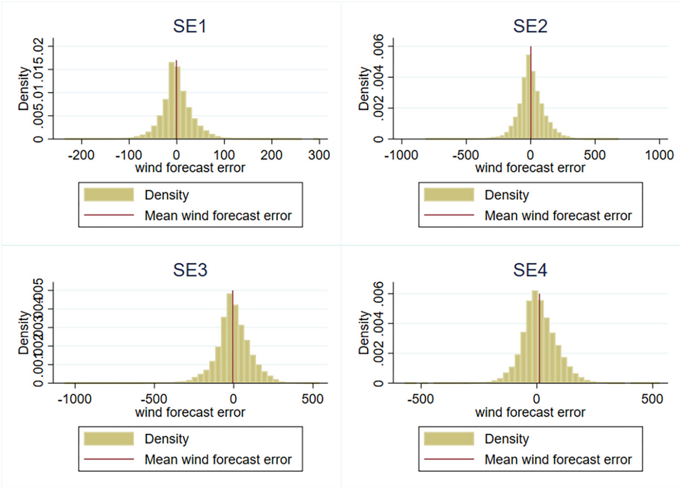


**Fig. 2.** Histograms of wind power forecast errors (in MWh) for each electricity price area in Sweden from 2015 to 2018.

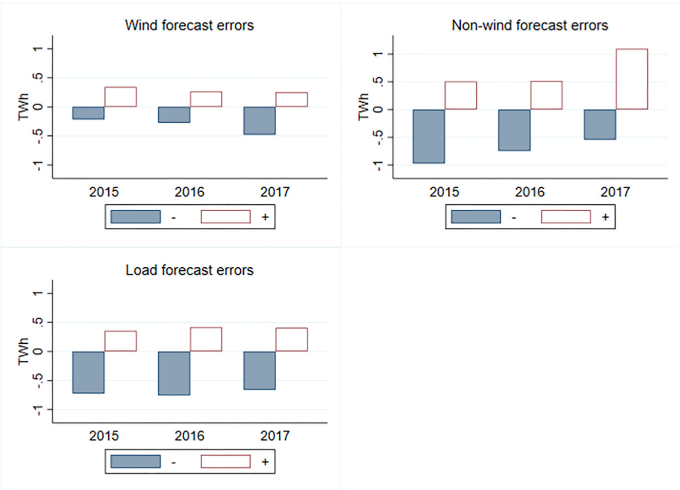


**Fig. 3.** The positive and negative wind forecast errors, non-wind forecast errors, and load forecast errors in Sweden from 2015 to 2017. *Notes:* "-" indicates the negative errors and "+" indicates the positive errors. The year 2018 is not included since data for this year is only available until June 2018.

According to Jaraitė et al. (2019), without intraday trading, this flexibility might not be utilized because flexibility on intraday and balancing markets can have different characteristics.[2] Additionally, Borggrefe and Neuhoff (2011) conclude that a well-functioning intraday market will prevent the abuse of market power and lower overall societal costs of wind power.

Despite these economic incentives to participate in intraday trading, given the increasing generation from variable renewable energy, there is a lot of evidence showing that many European intraday markets have small trading volumes that result in higher costs of imbalances and low market liquidity and efficiency (Henriot 2014; Mauritzen 2015; Scharff and Amelin 2016). For instance, Weber (2010) argues that, historically, the potential trading volume on the German intraday market, defined as the required short-term adjustments, should have been at least

[2] Balancing markets usually have higher requirements on balancing bids in terms of minimum bid size, activation times and purely physical fulfilment. This means that not all flexibility identified by market participants during the intraday trading period can be offered on the balancing market. In consequence, intraday markets provide a venue to access this flexibility and, hence, they should be regarded as complements rather than substitutes to balancing markets.

**Table 2**
Results of Granger causality tests.

| Dependent variables | (1) Intraday price premia | (2) Wind power f.e. | (3) Non-wind power f.e. | (4) Load f.e. | (5) Cross-region flows | (6) Forced outages |
|---|---|---|---|---|---|---|
| **SE1** | | | | | | |
| Intraday price premia | n/a | 28.89 | 183.4*** | 19.88 | 27.38 | n/a |
| Wind power f.e. | 25.61 | n/a | 29.87 | 60.47*** | 22.59 | n/a |
| Non-wind power f.e. | 81.75*** | 323.8*** | n/a | 53.61*** | 35.44** | n/a |
| Load f.e. | 24.84 | 646.7*** | 33.86* | n/a | 24.58 | n/a |
| Cross-region flows | 34.37* | 47.44*** | 34.74* | 33.00* | n/a | n/a |
| **SE2** | | | | | | |
| Intraday price premia | n/a | 61.75*** | 245.8*** | 34.10* | 38.18** | n/a |
| Wind power f.e. | 17.24 | n/a | 26.80 | 78.76*** | 20.45 | n/a |
| Non-wind power f.e. | 61.18*** | 253.0*** | n/a | 278.5*** | 40.71** | n/a |
| Load f.e. | 33.50* | 1003*** | 145.0*** | n/a | 25.34 | n/a |
| Cross-region flows | 37.46** | 99.60*** | 102.5*** | 55.32*** | n/a | n/a |
| **SE3** | | | | | | |
| Intraday price premia | n/a | 142.9*** | 228.0*** | 73.06*** | 54.64*** | 22.77 |
| Wind power f.e. | 15.60 | n/a | 38.99** | 88.30*** | 23.70 | 20.37 |
| Non-wind power f.e. | 60.01*** | 1891*** | n/a | 108.4*** | 53.89*** | 22.04 |
| Load f.e. | 48.59*** | 202.2*** | 58.49*** | n/a | 38.80** | 33.35* |
| Cross-region flows | 84.51*** | 193.9*** | 314.0*** | 125.5*** | n/a | 83.97*** |
| Forced outages | 22.25 | 33.73* | 13.61 | 21.53 | 84.49*** | n/a |
| **SE4** | | | | | | |
| Intraday price premia | n/a | 45.74*** | 39.13** | 35.42** | 22.63 | n/a |
| Wind power f.e. | 21.21 | n/a | 32.18* | 44.64*** | 23.18 | n/a |
| Non-wind power f.e. | 22.93 | 1058*** | n/a | 37.09** | 30.11 | n/a |
| Load f.e. | 32.31* | 284.0*** | 21.37 | n/a | 28.44 | n/a |
| Cross-region flows | 40.39** | 30.25 | 25.91 | 30.59 | n/a | n/a |

*Notes:* *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. The results are Wald statistics and follow $\chi^2$ distribution.
Wind power f.e. refers to wind power forecast errors. Non-wind power f.e. refers to non-wind power forecast errors, which is the total production error excluding wind power production errors. Load f.e. refers to load forecast errors.

two times larger than the actual trading volume. Besides, the liquidity on the intraday market might be asymmetric, such as in Denmark where wind shortfalls increase the probability of intraday trading, while wind surpluses make intraday trading less likely (Mauritzen 2015). According to Henriot (2014), the low liquidity of the intraday market is caused by the variable nature of wind forecasts, which discourages the players from trading in intraday markets, given available cheaper options in balancing markets.

One exception is the Spanish intraday market, which historically has had high trading volumes compared with other European markets. A possible explanation is that the intraday market design and electricity regulations are different in Spain (Chaves-Avila and Fernandes 2015). Chaves-Avila et al. (2013) argue that although wind farm owners prefer to participate in intraday markets to adjust production, the majority of electricity is still produced by the conventional generators who usually commit their production long ahead of time because of start-up costs and generation planning.

While a high level of liquidity has been viewed as a standard criterion for an effective intraday market, some scholars argue that an optimal intraday market should not target a large trading volume per se because economic agents behave according to the incentives that they receive from price signals (Henriot 2014; Karanfil and Li 2017). Karanfil and Li (2017) suggest that instead of focusing on the level of liquidity or intraday trade volumes, it is better to consider causality between price signals and market fundamentals. They use causality tests to access the functionality of the Danish intraday market and conclude that it is operating as intended, since wind and conventional generation forecast errors are the two fundamental factors that drive intraday prices, aside from day-ahead prices. There is a growing literature studying the efficiency in electricity markets, focusing on the price difference between the intraday and day-ahead markets (e.g., Ito and Reguant 2016; Woo et al. 2016; Karanfil and Li 2017; Tangerås and Mauritzen 2018). Our paper contributes to this emerging literature in energy economics by rigorously studying the price divergence between the electricity sequential markets and overall intraday market functionality in the case of Sweden. One novelty of our analysis is that it considers imbalances caused by unplanned nuclear power outages, which, to the best of our knowledge, has not been done before.

## 3. Swedish electricity markets and data

### 3.1. Swedish electricity markets

Swedish electricity markets consist of three sequential electricity markets: the day-ahead market, intraday market, and balancing market. The day-ahead and intraday markets are parts of the integrated Nordic-Baltic market Nord Pool.[3] In the day-ahead market, market actors submit their supply and demand bids for the next day no later than 12 noon. The market price is settled as a marginal price through a uniform auction at each hour. After the day-ahead price calculations, precise figures for unused cross-border transmission capacities are provided to the Nord Pool intraday market, where market actors can continue to trade and to balance their portfolios, if load or production forecasts turn out to be inaccurate. The intraday market opens for trading at 14:00 CET the day before and closes one hour before delivery. The market price is settled by continuous actions.

The day-ahead market is the primary electricity trading market and most Swedish electricity production is first allocated here. It plans for nearly 90% of the electricity consumed in Sweden (Swedish Energy Markets Inspectorate 2019). The intraday market is an adjustment market to the day-ahead market and its function is to keep the balance

[3] Nord Pool is a multinational power exchange market originally consisting of Sweden, Norway, Finland, Denmark, Latvia, Lithuania, and Estonia. Since June 12, 2018, the Nord Pool intraday market has been integrated with the European Cross-Border Intraday Market (XBID), through which all users can trade in 13 intraday markets, including Nordic and Baltic countries, Germany, Luxembourg, France, the Netherlands, Belgium, and Austria.

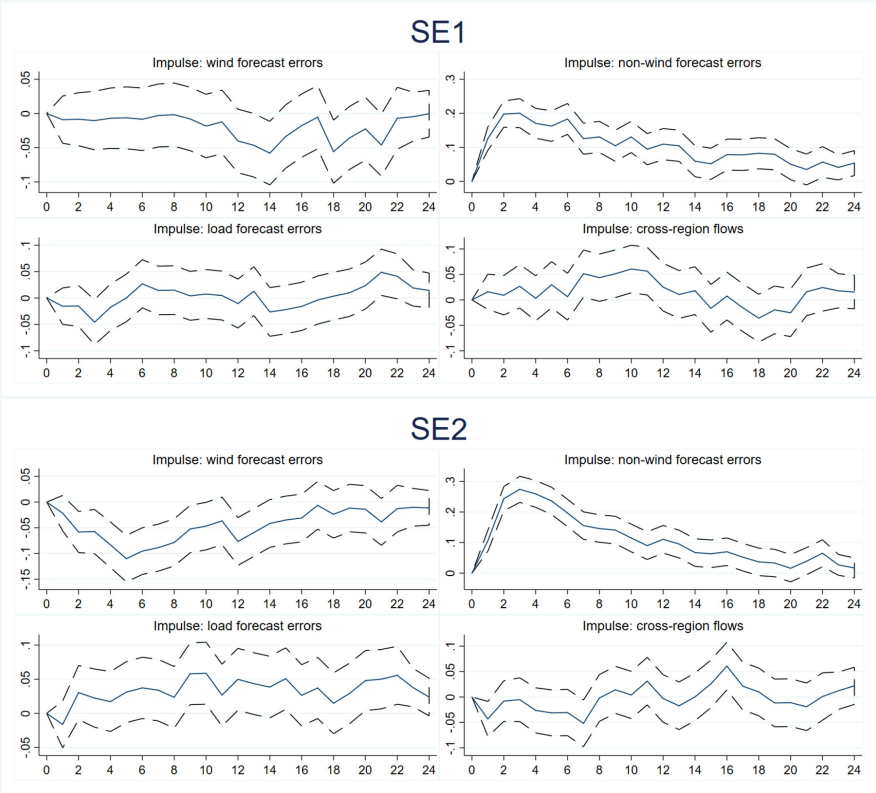


**Fig. 4.** Generalized impulse response functions of price premia in SE1 and SE2. Notes: Responses of price premia given one standard deviation shock to wind power forecast errors, non-wind forecast errors, load forecast errors, and cross-region flows, respectively, for an interval of 24 h after the shock. The solid line represents the point estimates, and the dashed dotted line represents the 95% confidence interval. The vertical axis represents the deviations of intraday price premia from their steady state measured in EUR/MWh.

between scheduled demand and supply. Compared to the day-ahead market, its trading volume is rather small. In 2018, the Swedish trading volume in the intraday market was only about 4% of the total electricity consumption in Sweden (Swedish Energy Markets Inspectorate 2019).

Because of the geographic transmission constraints, Sweden is divided into four electricity price areas: Luleå (SE1), Sundsvall (SE2), Stockholm (SE3), and Malmö (SE4). Within each area, the electricity price is determined by the demand and supply of electricity and the available transmission capacity. In each of these pricing zones, electricity generation mix is quite different. For example, in the middle part of Sweden (SE3), nuclear power dominates local generation capacity, while in the northern part of Sweden (SE1 and SE2), hydropower is dominating. Most of the electricity production is located in the north of Sweden, while most of the consumption is in the south of the country (Swedish Energy Markets Inspectorate 2014).

### 3.2. Data and descriptive analysis

We use time series data from the Nord Pool FTP server and the ENTSO-E Transparency Platform for the period 2015–2018.[4] In total, our dataset consists of 23,820 h-day observations. One of our key variables is the intraday price premium, which is defined as the difference between the intraday electricity price and the day-ahead electricity price, measured in euros per megawatt hour (EUR/MWh). The rest of the variables consist of the fundamental drivers of the intraday price premium, which include wind power forecast error, non-wind power forecast error, load (consumption) forecast error, cross-border electricity flow, transmission congestion, and forced outage of nuclear power plants. The majority of these drivers are measured in megawatt hours (MWh), except for transmission congestion, which is measured in megawatts (MW). All variables are available on an hourly basis for each electricity price area, excluding forced outage of nuclear power plants, which is only available for electricity price area SE3 because all Swedish nuclear power plants are located there.

Wind power forecast error is defined as the difference between the actual wind power production and the day-ahead wind power forecast. Similarly, non-wind power forecast error is the difference between the total actual and forecasted power production, excluding production from wind power. Nuclear plants forced outage is defined as the unavailable capacity of nuclear plants caused by an unplanned shutdown. In this paper, we will only consider forced outages since they drive most of the uncertainty in total outages. Using the sum of forced outages and planned outages can bias the estimated effects, since market players can adjust their production plans following public announcements of planned outages far ahead of the intraday market. We aggregate plant-level forced outages into total forced outages for each hour in

[4] We include data from January 24, 2015 to June 2, 2018.

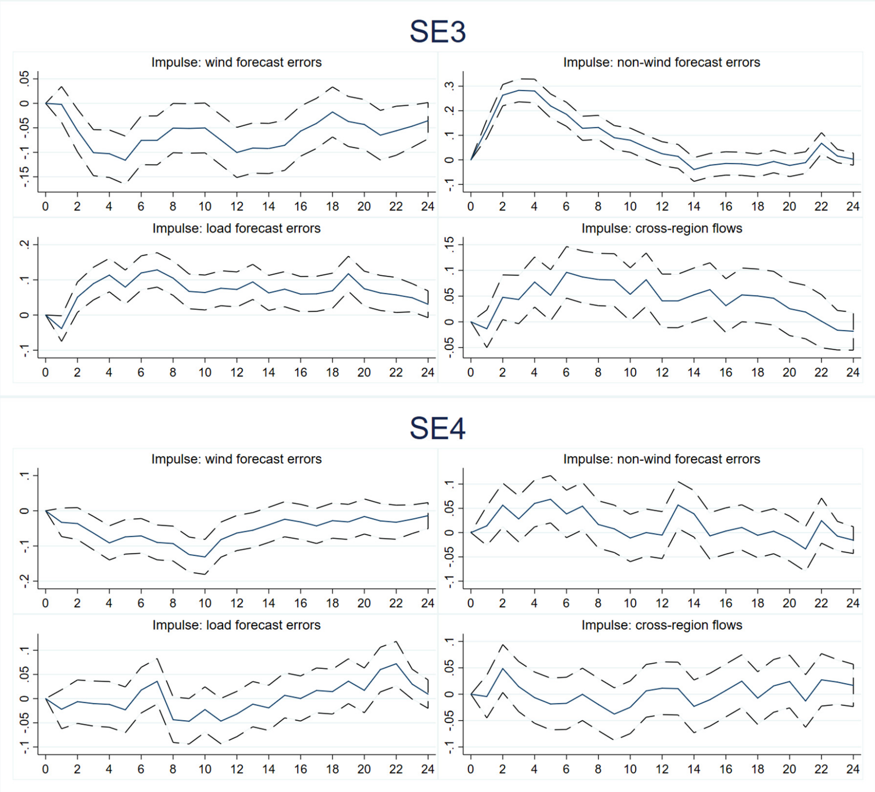


**Fig. 5.** Generalized impulse response functions of price premia in SE3 and SE4. Notes: Responses of price premia given one standard deviation shock to wind power forecast errors, non-wind forecast errors, load forecast errors, and cross-region flows, respectively, for an interval of 24 h after the shock. The solid line represents the point estimates, and the dashed dotted line represents the 95% confidence interval. The vertical axis represents the deviations of intraday price premia from their steady state measured in EUR/MWh.

electricity price area SE3. For modeling the imbalances caused by market fundamentals from the demand side, we include consumption (load) forecast error, which is measured as the difference between the actual and forecasted (day-ahead scheduled) consumption of electricity. Cross-region intraday flow measures the scheduled intraday electricity net import (import minus export) between a particular price area and its trading areas in the Nordic and Baltic countries.[5] To partly capture the potential congestion of transmission networks, we use the hourly initial capacity available in the intraday market. Data used to aggregate forced outages are obtained from the ENTSO-E Transparency Platform, while the rest of data are obtained from the Nord Pool FTP server.

Table 1 presents summary statistics of our variables for each Swedish electricity price area. A comparison of intraday price premia across all price areas shows that the mean of the hourly price premium is slightly below zero and it ranges from −0.147 to −0.460 EUR/MWh. However, the standard deviation of the price premium is rather large compared to the mean and we can easily reject the hypothesis that the mean value of the price premium is not zero for each Swedish electricity price area. Fig. 1 shows that hourly intraday premia are concentrated around zero in all price areas. According to the sequential electricity market design and current power generation mix in Sweden, intraday price premia could be positive as well as negative, depending on the excess of wind power supply and total demand in the system. A positive price premium indicates that the intraday electricity price is higher than the day-ahead electricity price, and vice versa. The direction of price change between the intraday and day-ahead markets depends on many things. For example, if there is a scarcity of balancing power, positive intraday price premia should appear more often and be larger than negative intraday price premia. However, this is not what we find in our data. Fig. 1 shows that extreme negative intraday price premia seem to happen at least as often as extreme positive intraday price premia, and this is true for almost all price areas. This could imply that there is no scarcity of balancing services in the Swedish electricity system.

Fig. 2 illustrates the distribution of wind power forecast errors. Positive values of wind power forecast errors indicate under-forecast. Conversely, negative values represent over-forecast. Fig. 2 shows that wind power forecast errors are symmetrically distributed around zero, except for a few negative extreme values in SE3, based on which, we draw the conclusion that over-forecast cases and under-forecast cases are balanced in all price areas.

Fig. 3 illustrates the annual total positive and negative wind forecast errors, non-wind forecast errors, and load forecast errors (TWh) in Sweden from 2015 to 2017. Wind power forecast errors and load forecast

5 There are in total fifteen price areas in the Nordic and Baltic countries, among which there are five regions in Norway (NO1, NO2, NO2, NO4, NO5), four in Sweden (SE1, SE2, SE3, SE4), two in Denmark (DK1,DK2), and the single bidding region countries, Finland (FI), Estonia (EE), Latvia (LV), and Lithuania (LT).

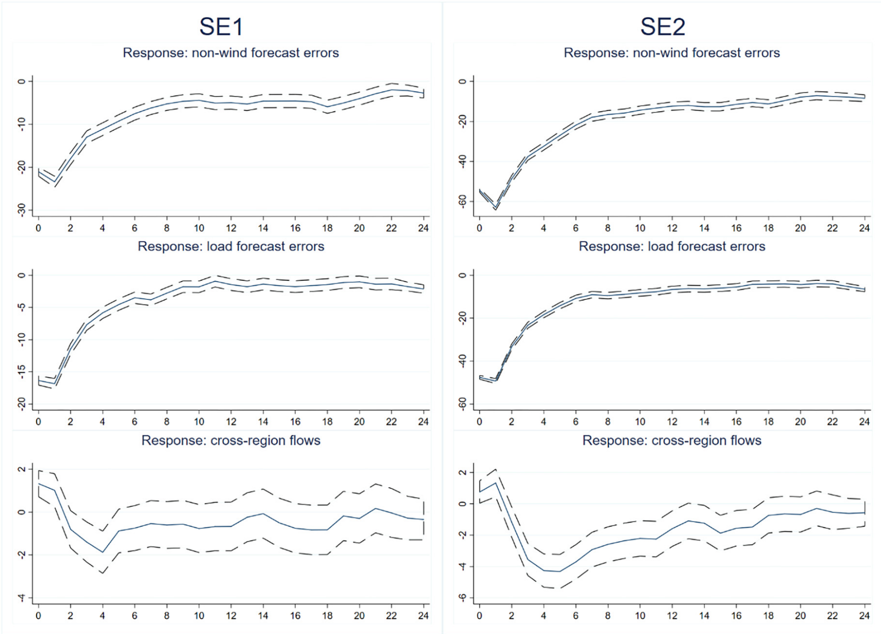


**Fig. 6.** Responses of market price drivers to wind power forecast errors in SE1 and SE2. *Notes:* Responses of market fundamentals (non-wind power forecast errors, load forecast errors, and cross-region flows), given one standard deviation shock to wind power forecast errors for an interval of 24 h after the shock. The solid line represents the point estimates, and the dashed dotted line represents the 95% confidence interval. The vertical axis represents the deviation of a corresponding response variable from its steady state measured in MWh.

errors are the major sources of the uncertainty that can cause deviations between day-ahead plans and actual power delivery. According to Fig. 3, load forecast errors don't vary much between years, but this is not true for wind forecast errors. There is a significant increase in total negative wind forecast errors (overestimation) over time. In 2017, the total negative wind power forecast error is almost twice the size of the one in 2015. This shows the increasing difficulty to forecast wind power production and potentially the increasing demand for balancing services.

## 4. Methods

To estimate the interactions of the intraday price premium with its market fundamentals in a dynamic setting, we use the vector autoregressive (VAR) framework. A VAR model is a multivariate and dynamic econometric model based on time series data. It requires that the time series are stationary or transformed into their stationary values. Assuming that the intraday price premium is the equilibrium outcome of the supply and demand for electricity in the intraday market, the major drivers from the supply side are wind power forecast error, non-wind power forecast error, and forced outage. Load forecast error represents the demand side price driver. In addition, intraday cross-region flow is another factor that could drive the price divergence between the intraday and day-ahead markets.

We estimate the following n-lag VAR model:

$$\boldsymbol{y}_{tr} = \boldsymbol{\mu} + \boldsymbol{\Pi}_1 \boldsymbol{y}_{t-1,r} + \boldsymbol{\Pi}_2 \boldsymbol{y}_{t-2,r} + \ldots + \boldsymbol{\Pi}_n \boldsymbol{y}_{t-n,r} + \epsilon_{tr}, \tag{1}$$

where $t = 1, \ldots T,\ r = 1, 2, 3, 4$

$$\boldsymbol{y}_{tr} = (p_{tr}, w_{tr}, nw_{tr}, l_{tr}, f_{tr})' \tag{2}$$

$\boldsymbol{y}_{tr}$ is the $(5 \times 1)$ vector of endogenous variables at hour $t$ in electricity price area $r$. $\boldsymbol{y}_{tr}$ consists of the intraday price premium ($p_{tr}$), wind power forecast error ($w_{tr}$), non-wind power forecast error ($nw_{tr}$), load forecast error ($l_{tr}$) and cross-region flow ($f_{tr}$).

We estimate the VAR(n) model separately for each electricity price area $r$, where $n$ represents the number of lags. In addition to the variables in Eq. (2), forced outage of nuclear plants is added in the analysis of price area SE3. Therefore, for price areas SE1, SE2, and SE4, we estimate the VAR model Eq. (1) with the endogenous variables as described in Eq. (2). For SE3, we estimate the VAR model Eq. (1) with the following endogenous variables:

$$\boldsymbol{y}_{t3} = (p_{t3}, w_{t3}, nw_{t3}, l_{t3}, f_{t3}, o_{t3})' \tag{3}$$

where $o_{t3}$ represents unplanned outage of nuclear power plants. Additionally, the congestion of transmission networks, $c_{tr}$, is introduced as an additional variable for robustness purposes in all measured VAR models.

The VAR model specified here is based on the assumption of stationarity, which requires the first and second moments of the time series matrix $\boldsymbol{y}_t$ ($E[\boldsymbol{y}_t]$ and $E[\boldsymbol{y}_t \boldsymbol{y}_{t-j}']$) to be independent of $t$. These conditions imply that each element of $\boldsymbol{y}_t$ is stationary. Consequently, we start by carrying out the stationary tests for each of the variables. Three types of stationary tests are applied here: modified augmented Dickey-Fuller (DF-GLS) test, Phillips and Perron's (PP) test, and Augmented Dickey-Fuller (ADF) test.[6] The null hypothesis for the tests is that a

[6] We apply augmented Dickey-Fuller (ADF) test (without drift and with trend), which is used to obtain the test statistics. Unlike other tests, the number of lagged difference terms needs to be specified in this test. To verify the conclusion drawn from ADF test and check the robustness of test results, we include two improved versions of stationary tests: Phillips and Perron's (PP) and modified augmented Dickey-Fuller (DF-GLS) tests. The PP test is robust to serial correlation by using the Newey and West (1987) heteroscedasticity- and autocorrelation-consistent covariance matrix estimator. The DF-GLS test gives more robust test results compared to ADF and PP tests, since it controls for a linear time trend.

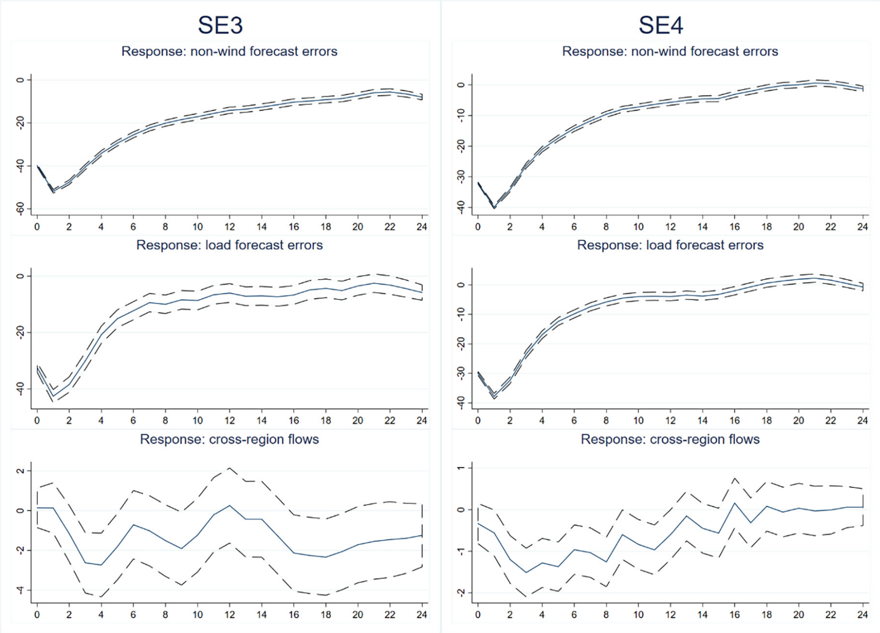


**Fig. 7.** Responses of market price drivers to wind power forecast errors in SE3 and SE4. Notes: Responses of market fundamentals (non-wind power forecast errors, load forecast errors, and cross-region flows), given one standard deviation shock to wind power forecast errors for an interval of 24 h after the shock. The solid line represents the point estimates, and the dashed dotted line represents the 95% confidence interval. The vertical axis represents the deviation of a corresponding response variable from its steady state measured in MWh.

variable has a unit root, while the alternative hypothesis is that the variable is stationary.

The lag length ($n$) for the VAR model is determined by using Akaike Information Criterion (AIC) before analyzing the VAR model (Akaike 1973). Granger causality tests and generalized impulse responses are used to summarize the dynamics of VAR estimation results. Intuitively, Granger causality tests are based on the idea that a cause cannot come after the effect (Granger 1969). Granger causality does not imply true causality but the forecasting ability. In our VAR model, if one variable, e.g., wind power forecast error ($w_t$), fails to Granger cause another variable, e.g., the intraday price premium ($p_t$), then we cannot reject that all of the coefficients on the lagged values of $w_t$ are zero in the equation for $p_t$. These linear restrictions can be tested by constructing Wald statistics. The Wald statistics testing the Granger causation of one variable on every other variable are used to summarize interactions between variables.

In addition to Granger causality tests, we apply generalized impulse responses (GIR)[7] to measure directions and magnitudes of the interactions between intraday price premia and market fundamentals. In general, impulse responses show how the response variable changes due to one standard deviation change in the impulse variable. Our primary interest is to investigate the effect of wind power forecast errors on intraday price premia.

## 5. Results and discussion

### 5.1. The results of unit root and Granger causality tests

Table A1 in the appendix presents the results of unit root tests. Columns (1,2) show the results of modified augmented Dickey-Fuller (DF-GLS) and Augmented Dickey-Fuller (ADF) tests, respectively. Columns (3, 4) show two test statistics for Phillips and Perron's (PP) tests. Each variable in every price area is treated as one time series. Together, these results indicate that all time series are stationary and integrated of order zero. Table A2 in the Appendix presents the choice of the lag length using Akaike's Information Criterion. The results suggest the choice of 23 lags (i.e., 23 h) is appropriate for each electricity price area.

Table 2 presents the results of Granger causality tests. Panels SE1, SE2, and SE4 are based on the endogenous variables in Eq. 2, and Panel SE3 is based on the endogenous variables in Eq. 3. Column (2) shows the test statistics for Granger causality of the wind power forecast error on all other variables, among which intraday price premium is our primary interest. We conclude that wind power forecast errors Granger cause intraday price premia in all electricity price areas except in SE1, where the absence of any effect in SE1 is likely to be explained by low wind power penetration in the north of Sweden. We also find that non-wind power forecast errors Granger cause intraday price premia in all price areas (see Column (3)). Column (6) presents the test results of another supply-side factor—forced outages of nuclear power plants, which are relevant only for electricity price area SE3. We show that these outages do not Granger cause intraday price premia, instead, they Grager cause cross-region flows. This finding might suggest that electricity shortages caused by an unplanned nuclear plant shutdown are likely to be mitigated by cross-region imports of electricity. This argument is further supported by our results from GIR function analysis (see discussion of Fig. 8 below).

Column (4) of Table 2 focuses on the effects on price premia from the demand side. It shows that load forecast errors Granger cause intraday prices to diverge from day-ahead prices in price areas SE2, SE3, and SE4. The non-significant effect in SE1 is associated with its small electricity demand relative to other price areas in Sweden. Column (5) shows that

[7] GIR was developed by Pesaran and Shin (1998). It is invariant to the ordering of the variables in the VAR model.


**Fig. 8.** Responses of cross-region flows to nuclear power forced outages in SE3. *Notes:* The solid line represents the point estimates, and the dashed dotted line represents the 95% confidence interval. The vertical axis represents the deviations of cross-region flows from their steady state measured in MWh.

cross-region flows Granger cause the price deviation between the intraday market and the day-ahead market in price areas SE2 and SE3.

Similar to Karanfil and Li's (2017) results, we find that in addition to intraday price premia, wind forecast errors are estimated to Granger cause non-wind forecast errors, load forecast errors and cross-region flows in nearly all electricity price areas (see column (2) in Table 2). We view these results as indicating that uncertainty in wind power production does not only cause the intraday price to diverge from the day-ahead price but also that it is associated with uncertainty in electricity production by other technologies, electricity consumption, and regional electricity trades. In this respect, electricity production and consumption forecast errors can be considered as measures of uncertainty. Uncertainty in wind power production causes generators of other electricity generation technologies to correct their production plans in the intraday market. Similarly, the consumption of electricity also responds to uncertainty in wind power production by adjusting away from the planned consumption levels.

### 5.2. Impulse responses

Additionally, we apply GIR function analysis[8] to assess the direction of the significant effects which we found by using Granger causality tests. First, we analyze the responses of intraday price premia after one standard deviation shock from each of the market fundamentals. After that, we look at the responses of the market fundamentals after one standard deviation shock from wind power forecast errors.

We begin by showing the responses of intraday price premia for each electricity price area in Figs. 4 and 5. It is evident that one standard deviation shock in wind power forecast errors has a negative effect on intraday price premia during the 24 h after the shock in electricity price areas SE2, SE3, and SE4.[9] These results are consistent with the findings from other studies (see, e.g., Karanfil and Li 2017; Spodniak, 2020) and provide some suggestive evidence on how the intraday market responds to imbalances caused by intermittent wind power. For example, when there is a positive shock in wind power forecast errors, i.e., more wind power is produced than forecasted, owners of wind power plants are willing to sell more electricity in the market, which will push down the electricity price in the intraday market. On the contrary, when the shock is negative, i.e., less wind power is produced than forecasted, owners of wind power plants need to buy electricity to meet their original production plans, which drives up the price in the intraday market.

Furthermore, this negative relationship between wind power forecast errors and intraday price premia might provide some insights on how balancing costs related to intraday trading could depend on the sign of wind power forecast error. When this error is positive (overproduction), intraday premia decrease, which presumably suggests that the correction of this error does not lead to higher balancing costs than in the case of the negative wind power forecast error (underproduction), which is associated with increasing intraday premia. However, from these results we cannot conclude about the actual size of balancing costs related to correction of wind power forecast errors in the intraday market, and whether these errors are fully absorbed in the intraday market.

The effect of non-wind power forecast errors on intraday price premia is found to be positive during the first 24 h in price areas SE1, SE2, and SE3. This result is in line with Karanfil and Li's (2017) study, which finds that forecast errors from combined heat and power (CHP) generation have positive effects on Danish intraday price premia. Generally, CHP generation has higher marginal costs compared to other generation technologies. An unexpected increase in CHP supply, for example, due to ramping-up for the imbalance caused by a sudden drop in wind power supply, will increase the electricity price in the intraday market relative to the electricity price in the day-ahead market. In our paper, non-wind power forecast errors send out the same signals as CHP forecast errors in the case of Denmark. Non-wind power in Sweden consists of nuclear power, hydropower, and other conventional power generation. Given stable (and low) marginal production costs for nuclear and hydropower generation, the variation in marginal production costs for non-wind power is mainly associated with other conventional power technologies, such as CHP. When there is a need for ramping-up, actual non-wind power production will increase, and because of its higher marginal production costs, electricity prices in the intraday market will increase. Therefore, a positive shock in non-wind power production with respect to its forecast increases the divergence between the intraday and day-ahead electricity prices.

The effect of load (consumption) forecast errors on intraday price premia is positive for electricity price area SE3 and slightly positive but very close to zero for other price areas. This positive relationship between consumption forecast errors and intraday price premia is in line with the fundamental electricity price setting model, which implies that when there is a sudden increase in the demand for electricity, the electricity price will increase to reflect the scarcity. Our results suggest that this scarcity is well absorbed in the Swedish intraday market.

Fig. 6 and Fig. 7 illustrate the effects of wind power forecast errors on the other market fundamentals, such as non-wind power forecast errors, load forecast errors, and intraday flows. It is evident that the responses of the same market fundamentals follow the same patterns across all electricity price areas. For instance, one standard deviation shock in wind power forecast errors has a significant and negative impact on non-wind forecast errors across all price areas. Intuitively, when there is more electricity supply from wind power relative to its forecast, the generation of electricity by using other power technologies will be reduced. Consequently, this will lead to lower non-wind forecast errors.

Furthermore, we find that a shock from wind power forecast errors has a negative and significant effect on cross-region flows for all price areas. Intuitively, if wind power production increases more than forecasted in one price area, there will be a lower net import of electricity from other price areas. This is in line with the findings of Karanfil and Li (2017).

Since the relationship between unplanned outages of nuclear power plants and cross-region flows might provide some explanations of why these outages have no effect on intraday price premia (see the results of the Granger causality test in Table 2, column 6), we additionally look at how cross-region flows respond to one standard deviation shock in forced nuclear power outages using GIR function analysis (see Fig. 8).

[8] The interpretations of impulse response are informative only when the impulse variable can Granger cause the response variable (Becketti 2013). For instance, recall that all variables except for forced outages of nuclear power plants Granger cause intraday price premia in SE3, which provides the foundation necessary for further analysis using impulse responses.

[9] For SE1, GIR results are not very informative, since wind power forecast errors do not Granger cause price premia (recall Table 2, Panel SE1).

**Table 3**
Results of Granger causality tests for robustness check.

| Dependent variables | (1) Intraday price premia | (2) Wind power f.e. | (3) Non-wind power f.e. | (4) Load f.e. | (5) Cross-region flows | (6) Congestions | (7) Forced outages |
|---|---|---|---|---|---|---|---|
| **SE1** | | | | | | | |
| Intraday price premia | n/a | 27.93 | 183.4*** | 14.63 | 28.75 | 60.70*** | n/a |
| Wind power f.e. | 26.88 | n/a | 26.54 | 60.42*** | 22.68 | 77.33*** | n/a |
| Non-wind power f.e. | 77.17*** | 339.7*** | n/a | 46.30*** | 38.89** | 214.9*** | n/a |
| Load f.e. | 22.00 | 654.60*** | 29.11 | n/a | 20.87 | 239.9*** | n/a |
| Cross-region flows | 34.31* | 47.62*** | 31.98 | 35.72** | n/a | 34.18* | n/a |
| Congestions | 31.83 | 92.08*** | 702.2*** | 550.5*** | 107.5*** | n/a | n/a |
| **SE2** | | | | | | | |
| Intraday price premia | n/a | 64.12*** | 245.2*** | 28.47 | 35.63** | 35.47** | n/a |
| Wind power f.e. | 17.38 | n/a | 20.04 | 78.36*** | 22.57 | 55.91*** | n/a |
| Non-wind power f.e. | 61.88*** | 240.7*** | n/a | 275.7*** | 37.35** | 125.2*** | n/a |
| Load f.e. | 31.06 | 1013*** | 140.4*** | n/a | 29.22 | 183.4*** | n/a |
| Cross-region flows | 36.64** | 96.07*** | 104.3*** | 55.67*** | n/a | 91.85*** | n/a |
| Congestions | 28.29 | 121.9*** | 210.3*** | 274.1*** | 105.6*** | n/a | n/a |
| **SE3** | | | | | | | |
| Intraday price premia | n/a | 134.9*** | 218.2*** | 71.53*** | 54.53*** | 49.82*** | 23.13 |
| Wind power f.e. | 14.93 | n/a | 37.46** | 61.18*** | 28.14 | 120.1*** | 20.70 |
| Non-wind power f.e. | 59.61*** | 1845*** | n/a | 112.4*** | 60.64*** | 102.3*** | 21.93 |
| Load f.e. | 49.51*** | 197.7*** | 45.75*** | n/a | 33.19* | 411.8*** | 32.68* |
| Cross-region flows | 84.62*** | 185.6*** | 301.1*** | 129.6*** | n/a | 55.15*** | 85.10*** |
| Congestions | 33.79* | 132.8*** | 145.1*** | 306.1*** | 156.9*** | n/a | 16.44 |
| Forced outage | 22.12 | 33.09* | 13.32 | 20.20 | 86.08*** | 15.30 | n/a |
| **SE4** | | | | | | | |
| Intraday price premia | n/a | 47.52*** | 39.44** | 35.02* | 22.64 | 28.35 | n/a |
| Wind power f.e. | 20.57 | n/a | 25.27 | 23.83 | 17.29 | 163.2*** | n/a |
| Non-wind power f.e. | 23.05 | 1071*** | n/a | 23.66 | 27.11 | 127.1*** | n/a |
| Load f.e. | 31.77 | 307.8*** | 23.94 | n/a | 23.72 | 532.5*** | n/a |
| Cross-region flows | 39.87** | 33.14* | 20.15 | 27.91 | n/a | 103.0*** | n/a |
| Congestion | 23.79 | 31.06 | 24.83 | 248.5*** | 133.7*** | n/a | n/a |

*Notes*: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. The results are Wald statistics and follow $\chi^2$ distribution.
Wind power f.e. refers to wind power forecast errors.
Non-wind power f.e. refers to non-wind power forecast error, which is the total production error excluding wind power production error. Load f.e. refers to load forecast errors.

It shows that the sudden change in these outages is positively correlated with cross-region flows. This result might suggest that when nuclear power plants suddenly cut down production because of unplanned outages, one way to balance the electricity market in SE3 is to increase the import of electricity from other regions.

### 5.3. Robustness test

In the baseline estimation, we estimate the effects of wind power forecast errors on intraday price premia based on the VAR models using non-wind power forecast errors, load forecast errors, forced outages of nuclear power plants, and cross-region flows (net import). We perform a robustness check where we include a proxy for network congestion as an additional variable. The results of unit root tests are presented in Table 1, which show that the congestion variable is stationary in all price areas. Besides, the choice of the lag length is 23 h based on the results of Akaike's Information Criterion as reported in Table A3 in the Appendix.

Table 3 presents the results of the Granger causality tests. Overall, the test statistics of robustness exercise are consistent with the ones from the baseline estimation (see Table 2). Price divergence between the intraday and day-ahead markets can more or less be explained by wind and non-wind power forecast errors, load forecast errors, forced outages, cross-region flows and congestions in each price area. As before, wind power forecast errors Granger cause intraday price premia in electricity price areas SE2, SE3, and SE4. Non-wind power forecast errors are estimated to have impacts on intraday price premia in all price areas. Load forecast errors and cross-region flows also show evidence of having impacts on intraday price premia in the SE3 price area. Again, unplanned nuclear power plant outages have no impact on intraday price premia, but the effect is significant on cross-region flows. Based on the results as reported in column (6) of Table 3, we can conclude that congestion affects intraday price premia in all price areas except SE4, and it Granger causes all other intraday market determinants across all price areas.

The GIR analysis, which is based on the extended model, provides additional evidence on the robustness of the effects of the major price drivers on intraday price premia. Figs. B1–B4 in the Appendix present the effects of the main price drivers on intraday price premia in price areas SE1–SE4 by using GIR analysis. We can conclude that the effects of the main price drivers on the divergence between the electricity price in the intraday market and the electricity price in the day-ahead market have the same sign in the robustness exercise as in the baseline model in each price area. For instance, wind forecast errors have significant and negative impacts on intraday price premia, and non-wind forecast errors have significant and positive instantaneous effects on intraday price premia in most price areas except for SE4.

In addition, we illustrate the effect of congestion on intraday price premia. We find that a positive shock from congestion, which is equivalent to an increase in the hourly initial capacity available on the intraday market, will reduce intraday price premia for the first six hours in price areas SE1 and SE2, while it will increase intraday price premia instantaneously in price area SE3 and will have no effect in SE4.[10] The results on congestion indicate that the initial capacity available in the intraday market can partly explain the price divergence between intraday and day-ahead markets. This result, along with results from other price drivers, suggests that the Swedish intraday market is sending price signals to incentivize electricity producers and consumers to participate in this market to reduce imbalances.

[10] Column (6) in Table 3 shows that congestion does not affect price premia in price area SE4. Thus, the GIR result for congestion in Figure B4 of the Appendix is not informative.

## 6. Conclusions

This paper uses detailed Swedish data to provide a case study of the functioning of intraday markets. As shares of intermittent renewable energy are getting substantial in Sweden, the intraday market becomes more essential in providing balancing services and flexibility in the system. We use the approach suggested by Karanfil and Li (2017) to assess the importance of the Swedish intraday market by studying the causality between price signals and market fundamentals. By doing so, we are able to investigate whether the intraday market rewards its participants, as it should if it is efficient. To understand this, we have looked at price formation in the intraday market and its relation to the price formation in the day-ahead market. We have analyzed, imbalances caused by wind power and other power-generating technologies, and the interconnection system.

Similar to Karanfil and Li's findings, our results suggest that several market fundamentals— wind power forecast errors, non-wind power forecast errors, load forecast errors, and cross-region flows—could explain the divergence between electricity prices in the Swedish intraday and day-ahead markets. Seemingly, wind forecast errors are "corrected" by joint responses from cross-region intraday power flows and adjustments of non-wind power generation and electricity consumption. These results are robust to adding the congestion as an additional price driver in our empirical models.

One of our key findings is that the relationships between wind power forecast errors and intraday price premia are found to be negative in three out of four Swedish electricity price areas (SE2, SE3, and SE4). This estimated negative relationship has two implications. First, it indicates that when the actual wind power production diverges from its forecast, the price of electricity in the intraday market is going to incorporate this information and be differentiated from the day-ahead market price. In particular, when the actual wind power production is larger than its forecast, market participants are willing to pay a lower electricity price on the intraday market compared to the price of electricity on the day-ahead market and vice versa. Second, it provides some insights on how the costs of balancing in the intraday market could depend on the sign of wind power forecast errors. Intraday price premia can be considered as balancing costs for electricity producers and consumers who participate in the intraday market. Our results suggest that a positive wind power forecast error, which occurs when there is an overproduction of wind power, may lead to lower intraday price premia. Conversely, a shortfall of wind power (negative wind forecast error) is expected to increase intraday price premia. Thus, we can imply that the costs of balancing related to trading in the intraday market might be smaller when the value of wind power forecast error is positive instead of being negative. However, from these results we cannot conclude about the actual size of balancing costs related to correction of wind power forecast errors in the intraday market, and whether these errors are fully absorbed in the intraday market. Furthermore, we have found that unplanned (forced) outages of the Swedish nuclear power plants, which occur only in price area SE3, have no effect on intraday price premia. The possible explanation of this result is that imbalances caused by these outages are mediated by electricity flows from other price areas to price area SE3, which is the best-connected price area in Sweden. Consequently, this type of outage is less likely to influence electricity prices in the Swedish intraday market.

Together, our results shed light on the Swedish intraday market's role in accommodating intermittent renewable energy. Price signals from the intraday market adequately incentivize trading decisions to reduce imbalances in scheduled production or consumption. That is to say, deviations from intermittent power generation are absorbed by other market fundamentals, and intraday price premia respond to these deviations and send out correct price signals based on scarcity pricing. Suppose a rapid growth of wind power in Sweden will continue, as well as a likely increasing number of participants on the demand side, intraday markets will play more important roles than in the past. Hence, we see a need for future research that tries to better understand the functioning of intraday markets by analyzing their microstructure in more detail, which could explain how we can increase their popularity among smaller market participants on the demand and supply sides.

## Credit author statement

All authors participated equally in every part of the research process.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2021.105159.

## Appendix

**Table A1**
Results of unit root tests.

| | (1) DF-GLS | (2) ADF | (3) PP $Z\_\tau$ | (4) PP $Z\_\rho$ |
|---|---|---|---|---|
| Price premium | | | | |
| SE1 | −53.58*** | −52.09*** | −84.23*** | −12,197*** |
| SE2 | −61.66*** | −53.49*** | −79.86*** | −11,018*** |
| SE3 | −59.08*** | −51.05*** | −73.80*** | −9552*** |
| SE4 | −69.42*** | −57.19*** | −95.08*** | −14,962*** |
| Wind power forecast error | | | | |
| SE1 | −52.82*** | −47.32*** | −46.00*** | −3915*** |
| SE2 | −50.65*** | −43.67*** | −42.00*** | −3297*** |
| SE3 | −38.23*** | −30.35*** | −30.33*** | −1783*** |
| SE4 | −55.05*** | −39.76*** | −38.93*** | −2870*** |

**Table A1** (*continued*)

| | (1) DF-GLS | (2) ADF | (3) PP $Z\_\tau$ | (4) PP $Z\_\rho$ |
|---|---|---|---|---|
| Non-wind power forecast error | | | | |
| SE1 | −49.75*** | −65.74*** | −68.10*** | −8186*** |
| SE2 | −47.05*** | −47.40*** | −44.28*** | −3646*** |
| SE3 | −38.65*** | −34.77*** | −28.78*** | −1593*** |
| SE4 | −49.19*** | −38.51*** | −36.89*** | −2589*** |
| Load forecast error | | | | |
| SE1 | −57.12*** | −82.68*** | −95.79*** | −15,912*** |
| SE2 | −41.55*** | −52.94*** | −53.57*** | −5259*** |
| SE3 | −39.20*** | −43.27*** | −42.55*** | −3391*** |
| SE4 | −41.41*** | −39.37*** | −37.85*** | −2708*** |
| Flow | | | | |
| SE1 | −42.24*** | −46.61*** | −47.05*** | −4124*** |
| SE2 | −49.42*** | −59.52*** | −61.68*** | −6842*** |
| SE3 | −40.59*** | −45.96*** | −46.62*** | −4059*** |
| SE4 | −72.44*** | −86.43*** | −91.75*** | −13,895*** |
| Congestion | | | | |
| SE1 | −37.64*** | −28.14*** | −31.37*** | −1921*** |
| SE2 | −31.02*** | −22.77*** | −26.89*** | −1427*** |
| SE3 | −31.53*** | −19.60*** | −23.94*** | −1138*** |
| SE4 | −34.79*** | −26.58*** | −27.15*** | −1444*** |
| Outage | | | | |
| Forced outage SE3 | −56.04*** | −60.58*** | −60.67*** | −6532*** |

*Notes:* *** represents 1% significance level. DF-GLS: Dickey-Fuller test modified by Elliot, Rothenberg, and Stock (1996). ADF: augmented Dickey-Fuller test with the trend and no lags. PP: Phillips-Perron tests with two statistics. ADF tests yield the same results when we include the different numbers of lags up to 10. DF_GLS already include lags. PP has no lags.

**Table A2**
Lag length selection for the baseline models.

| lag | SE1 | SE2 | SE3 | SE4 |
|---|---|---|---|---|
| 0 | 51.972 | 55.375 | 65.997 | 51.385 |
| 1 | 47.565 | 49.906 | 57.312 | 45.007 |
| 2 | 47.434 | 49.794 | 57.164 | 44.860 |
| 3 | 47.392 | 49.749 | 57.109 | 44.843 |
| 4 | 47.383 | 49.743 | 57.063 | 44.840 |
| 5 | 47.377 | 49.737 | 57.041 | 44.839 |
| 6 | 47.374 | 49.730 | 57.027 | 44.838 |
| 7 | 47.372 | 49.724 | 57.014 | 44.798 |
| 8 | 47.369 | 49.721 | 57.010 | 44.797 |
| 9 | 47.366 | 49.719 | 57.004 | 44.797 |
| 10 | 47.362 | 49.718 | 57.000 | 44.788 |
| 11 | 47.361 | 49.717 | 56.999 | 44.787 |
| 12 | 47.361 | 49.716 | 56.995 | 44.786 |
| 13 | 47.36 | 49.714 | 56.990 | 44.779 |
| 14 | 47.359 | 49.711 | 56.989 | 44.777 |
| 15 | 47.359 | 49.711 | 56.987 | 44.775 |
| 16 | 47.358 | 49.710 | 56.985 | 44.769 |
| 17 | 47.358 | 49.708 | 56.982 | 44.766 |
| 18 | 47.358 | 49.706 | 56.979 | 44.762 |
| 19 | 47.357 | 49.703 | 56.977 | 44.755 |
| 20 | 47.355 | 49.700 | 56.970 | 44.749 |
| 21 | 47.353 | 49.696 | 56.961 | 44.740 |
| 22 | 47.348 | 49.687 | 56.951 | 44.729 |
| 23 | 47.344* | 49.679* | 56.939* | 44.718* |

Notes: * indicates the optimal lag. The selection is based on Akaike Information Criterion (AIC) and conducted separately for each electricity price area. Endogenous variables in eq. (2) are used for the bidding areas SE1, SE2, and SE4. Endogenous variables in eq. (3) are used for the bidding area SE3.

**Table A3**
Lag length selection for models in robustness exercise.

| lag | SE1 | SE2 | SE3 | SE4 |
|---|---|---|---|---|
| 0 | 68.533 | 72.775 | 83.805 | 68.214 |
| 1 | 61.81 | 64.638 | 72.141 | 59.402 |
| 2 | 61.341 | 64.298 | 71.618 | 59.114 |
| 3 | 61.296 | 64.235 | 71.561 | 59.092 |
| 4 | 61.285 | 64.226 | 71.515 | 59.088 |
| 5 | 61.278 | 64.217 | 71.49 | 59.086 |
| 6 | 61.268 | 64.203 | 71.471 | 59.084 |
| 7 | 61.243 | 64.183 | 71.444 | 59.029 |

(continued on next page)

**Table A3** (*continued*)

| lag | SE1 | SE2 | SE3 | SE4 |
|---|---|---|---|---|
| 8 | 61.236 | 64.175 | 71.436 | 59.023 |
| 9 | 61.233 | 64.173 | 71.429 | 59.022 |
| 10 | 61.229 | 64.171 | 71.424 | 59.014 |
| 11 | 61.227 | 64.168 | 71.422 | 59.012 |
| 12 | 61.225 | 64.165 | 71.418 | 59.011 |
| 13 | 61.224 | 64.163 | 71.409 | 59.001 |
| 14 | 61.218 | 64.157 | 71.401 | 58.996 |
| 15 | 61.207 | 64.149 | 71.386 | 58.99 |
| 16 | 61.187 | 64.136 | 71.361 | 58.966 |
| 17 | 61.157 | 64.117 | 71.332 | 58.946 |
| 18 | 61.112 | 64.095 | 71.303 | 58.918 |
| 19 | 61.078 | 64.082 | 71.292 | 58.895 |
| 20 | 61.071 | 64.077 | 71.281 | 58.887 |
| 21 | 61.059 | 64.073 | 71.268 | 58.873 |
| 22 | 61.044 | 64.065 | 71.258 | 58.859 |
| 23 | 61.038* | 64.051* | 71.239* | 58.846* |

Notes: * indicates the optimal lag. The selection is based on Akaike Information Criterion (AIC) and conducted separately for each electricity price area. Endogenous variables in eq. (2) and the additional variable Congestions are used for the bidding areas SE1, SE2, and SE4. Endogenous variables in eq. (3) and the additional variable Congestions are used for the bidding area SE3.


**Fig. B1.** Robustness check—Generalized Impulse Response of price premia in SE1. *Notes:* Responses of price premia, given one standard deviation shock to wind power forecast errors, non-wind forecast errors, load forecast errors, cross-region flows, and congestions, respectively, for an interval of 24 h after the shock. The solid line represents the point estimates, and the dashed dotted line represents the 95% confidence interval. The vertical axis represents the deviations of intraday price premia from their steady state measured in EUR/MWh.


**Fig. B2.** Robustness check—Generalized Impulse Response of price premium in SE2. *Notes:* Responses of price premia, given one standard deviation shock to wind power forecast errors, non-wind forecast errors, load forecast errors, cross-region flows, and congestions, respectively, for an interval of 24 h after the shock. The solid line represents the point estimates, and the dashed dotted line represents the 95% confidence interval. The vertical axis represents the deviations of intraday price premia from their steady state measured in EUR/MWh.


**Fig. B3.** Robustness check—Generalized Impulse Response of price premium in SE3. *Notes:* Responses of price premia, given one standard deviation shock to wind power forecast errors, non-wind forecast errors, load forecast errors, cross-region flows, and congestions, respectively, for an interval of 24 h after the shock. The solid line represents the point estimates, and the dashed dotted line represents the 95% confidence interval. The vertical axis represents the deviations of intraday price premia from their steady state measured in EUR/MWh.


**Fig. B4.** Robustness check—Generalized Impulse Response of price premium in SE4. *Notes: Responses of price premia, given one standard deviation shock to wind power forecast errors, non-wind forecast errors, load forecast errors, cross-region flows, and congestions, respectively, for an interval of 24 h after the shock. The solid line represents the point estimates, and the dashed dotted line represents the 95% confidence interval. The vertical axis represents the deviations of intraday price premia from their steady state measured in EUR/MWh.*

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# Does income redistribution prevent residential segregation?☆

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A B S T R A C T

Living in low-income neighborhoods can have adverse effects. Public policies that reduce income inequality might prevent residential segregation by income. However, previously documented associations between income inequality and residential segregation may not reflect residential sorting effects. We use rich full-population data for Sweden 1990–2017 and take advantage of how in-moving residents change the municipal income composition to rule out the influence of reverse causation and mechanical effects. We find that changing taxes and transfers has limited residential sorting effects on segregation. However, our results strongly suggest that raising the education levels of low-income residents is effective for fighting segregation.



## 1. Introduction

Economists have mapped the rising income inequality in the industrialized world since World War II and attributed much of this trend to increasing top incomes (see the review by Atkinson et al. 2011).[1] A broad literature suggests that inequality has negative consequences on economic, health, and social outcomes at the individual level (see the review by Neckerman and Torche 2007). Recently, there has been growing attention on spatial inequality between regions within countries (Diamond, 2016; Gaubert et al., 2021). Income inequality between residents across neighborhoods within cities, typically referred to as residential segregation by income, is another type of spatial inequality.[2]

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[1] Piketty et al. (2006), Piketty (2011, 2013), and Saez and Zucman (2016) have presented deeper analyzes of potential causes of the rising inequality.

[2] Massey and Denton (1988), Jargowsky (1996), Massey and Fischer (2003), Ioannides (2004), Reardon and O'Sullivan (2004), and Wheeler and La Jeunesse (2008) have discussed how to measure segregation and identified trends over time in the U.S.

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Segregation could create some neighborhoods with a high share of low-income residents. Researchers have found empirical evidence showing that living or growing up in such neighborhoods has adverse effects on, e.g., college attendance and earnings, potentially because of less beneficial social networks (Katz et al., 2001; Kling et al., 2007; Ludwig et al., 2012; Chetty et al., 2016). Thus, segregation is likely harmful to residents with neighborhood effects serving as a mediating channel.

If everybody has the same income, then there cannot be any segregation. However, income inequality does not necessarily generate residential segregation since low- and high-income residents may live in a spatially mixed way. The similar effects of inequality and segregation raise the empirical question of whether inequality leads to segregation and whether segregation is the crucial link between inequality and its negative consequences. In inequality research, this link is often conceptually recognized, e.g., regarding the effects of inequality on outcomes such as violent crime (Kelly, 2000) and trust (Gustavsson and Jordahl, 2008). However, few studies empirically account for this link; the infant mortality study by Mayer and Sarin (2005) is an exception.

There are only a handful of empirical studies of income inequality as a driver of residential segregation (Mayer, 2001; Watson, 2009; Reardon and Bischoff, 2011; Chen et al., 2012). These studies used decennial census data at the neighborhood level for cities (mostly in the U.S.) and they found interesting correlations between changes in inequality and segregation. However, they provide insufficient guidance for policymakers who want to use different types of public policies that reduce inequality for preventing segregation due to residential sorting across neighborhoods.

We have access to geo-coded administrative data at the individual level covering the entire population in Sweden for each year from 1990 to 2017. During this period, Sweden experienced unprecedented growth in income inequality concurrent with a welfare state deterioration. These trends are remarkable even in an international comparison.[3] We leverage the data and contribute to existing research by identifying how changing different determinants of income inequality affects residential sorting and segregation. We focus on the role of determinants related to public redistribution and socio-demographic composition. Our results provide new and detailed insights for policymakers who want to fight segregation, e.g., regarding whether they should equalize abilities to consume or to earn income, and regarding the importance of poverty versus affluence reduction.

Housing quality (e.g., living area and amenities) and access to public goods (e.g., schools and recreational facilities) vary across neighborhoods. Tiebout (1956) showed that if residents have different abilities and willingness to pay for housing quality and public goods, then systematic neighborhood sorting patterns will emerge. Schelling (1969) proposed an alternative explanation to residential segregation: Residents who are similar, e.g., with respect to income or education levels, could prefer to reside in the same neighborhoods. In contrast to Tiebout's theory, residential preferences (willingness to pay) can depend on the income level for reasons unrelated to the ability to pay. For instance, high-income residents typically have higher education levels and could therefore value school quality more than others with the same ability to pay. They might also prefer to live and interact with similar-minded or care more about the neighborhood of residence as a status marker.

Both Tiebout (1956) and Schelling (1969) predicted that residential preferences and choices vary with income levels. In this sense, income inequality or its determinants affect residential sorting and thereby segregation. From a policy perspective, it is crucial to understand the determinants that matter. However, when there is existing segregation, the development of inequality and segregation over time may be associated in two ways unrelated to residential sorting: First, segregation may reinforce inequality leading to reverse causation because neighborhood effects could generate differential income growth in low- and high-income neighborhoods. Moreover, urban planning can affect neighborhood housing quality and public goods. In the models from Tiebout and Schelling, for a given income distribution, such neighborhood characteristics also affect residential choices. Once policies affect segregation, neighborhood effects can generate subsequent effects on inequality. Second, changing economic conditions have varying effects on individuals and therefore affect neighborhoods differentially depending on their residential composition. For instance, new welfare benefits to low-income families mechanically reduce both inequality and segregation.

Unlike previous research, we rule out reverse causation and mechanical effects enabling us to offer policy recommendations on how to reduce current inequality to prevent future segregation due to residential sorting across neighborhoods. Our novel strategy takes advantage of the fact that new residents arriving from other municipalities are not part of existing segregation, but they do affect the municipal income composition and inequality. We use the municipality-by-year variation in this external inequality shock, and we identify subsequent segregation effects due to active residential choices of the in-movers and the original population's responses after the inequality shock.[4]

Public redistribution through taxes and transfers is a determinant of disposable incomes. These incomes reflect abilities to consume and pay for housing. Such abilities generate the type of segregation Tiebout (1956) mentioned. Previous literature focused on inequality and segregation in terms of disposable incomes. However, disposable income is pre-tax income adjusted for taxes and transfers. To evaluate whether public redistribution can prevent segregation, one needs to account

[3] For disposable incomes, our data show that inequality between residents within municipalities (standard deviation of the logarithm of income) increased by 66%, and residential segregation (neighborhood sorting index) increased by 37%. Data from the World Bank reveal that the national Gini coefficient increased from 24.9 to 30.0 between 1992 and 2018 in Sweden. In comparison, the Gini coefficient increased from 34.5 to 40.4 between 1979 and 1993 (and the trend was flat thereafter) in the U.S.

[4] Migration has previously been exploited as an exogenous shock to the population composition, e.g., for studying the effects of ethnic composition in a geographical area (Edin et al., 2003; Andersson et al., 2021).

for the fact that pre-tax income and its determinants may have separate direct effects on segregation. Such determinants include individual characteristics such as age, education, and innate ability as well as structural factors affecting local labor market conditions, e.g., institutional, organizational, and technological factors.

Unlike previous data, we observe pre-tax incomes in our rich data allowing us to control for pre-tax income effects. We rely on the remaining municipality-by-year variation in the distribution of disposable incomes due to changes in the tax and transfer system for identifying the influence of disposable income inequality on residential segregation.[5]

We find a positive correlation between changes in *disposable income* inequality (standard deviation of log income) and segregation (neighborhood sorting index). However, our main result is that the correlation disappears once ruling out reverse causation and mechanical effects. Thus, unequal consumption abilities were not decisive for residential sorting in a way that can explain growing income differences between neighborhoods. Finding limited residential sorting effects of disposable income inequality is discouraging in terms of fighting overall segregation via public redistribution.

Even with homogenous disposable incomes due to perfect public redistribution, residents might prefer neighborhoods with others who are similar to themselves, e.g., with respect to pre-tax incomes reflecting abilities to earn income (in the labor and capital markets). To prevent this type of segregation following from Schelling's (1969) theory, policymakers could target the determinants of pre-tax income inequality such as education levels.

We find that increasing *pre-tax income* inequality over time can account for the entire surge in segregation since the 1990s. Particularly, the growing municipal shares of residents with low pre-tax incomes can explain most of the rising concentration of such individuals in certain neighborhoods. However, most of the influence of inequality change on segregation change due to residential sorting disappears when controlling for municipal changes in the education composition of residents.[6] Hence, increasing pre-tax incomes of low-income residents by raising their levels of education and thereby earning abilities is most likely effective for fighting segregation.

The next section describes our data and the institutional background. It also explores overall income inequality and residential segregation trends over time. Section 3 outlines our empirical strategy. Section 4 reports our estimates for overall inequality and segregation. Section 5 distinguishes the effects of inequality on segregation along different parts of the income distribution. The final section provides a concluding discussion with a focus on policy implications.

## 2. Data and background

### *2.1. Data and institutional background*

We use annual data from the GEO-Sweden database (1990–2017). These data cover the entire population of around 10 million inhabitants (in 2017) and contain income variables from the tax authorities including information on taxes and transfers. We link observations for each person over time using his or her social security number, and we then link the observations to other administrative registers containing, e.g., demographic background variables. While Swedish social scientists have frequently used good microdata before,[7] a unique additional feature of GEO-Sweden is that it geographically links individuals to the real estate where they reside (via their registered addresses). Thus, some researchers have used GEO-Sweden to study neighborhood effects.[8] GEO-Sweden also allows us to pinpoint residential moving patterns.[9]

Sweden has three levels of government: central, county, and municipal levels. The institutional setting is streamlined across administrative units. The 290 municipalities are each organized around a central town or village. They are independent actors playing a key role in Swedish society providing daycare, education, care of the elderly, and other welfare services. While we measure income inequality at the municipal level, we characterize residential segregation by income for a municipality as differences in income distributions across neighborhoods within the municipality. We let the 5986 Swedish DESO-areas represent our neighborhood units.[10] These units were constructed to each contain about 1700 residents in 2017.[11]

Previous segregation research (e.g., Reardon and Bishoff, 2011) frequently used families or households as income units; here, we use each individual as an income unit to avoid several complications. First, we do not need to address the fact that there are many unmarried cohabiting couples with or without children in Sweden. Second, we circumvent the issue of unstable and not fully comparable units over time due to the high and changing divorce rate. Third, we do not need to account for differences in the number of members across families or households. However, we provide sensitivity tests of

[5] In public finance research, the tax and transfer system or its change is regularly assumed to be an exogenous determinant of an individual's disposable income (see, e.g., the critical review by Saez et al. 2012).

[6] In contrast, our estimates are insensitive to accounting for effects due to the country-of-birth composition in municipalities. A deeper study of residential ethnic segregation is beyond the scope of this paper.

[7] Edin and Fredriksson (2000) compiled an individual longitudinal data set (around 300,000 individuals) and sparked a wider use of Swedish administrative data in economic research.

[8] Examples of studies include those by Edin et al. (2003), Galster et al. (2008), and Hedman et al. (2015).

[9] Andersson and Turner (2014) used this feature to study moving chains in Stockholm.

[10] DESO is an acronym for "demografiska statistikområden" meaning "demographic statistical areas". Our results are insensitive to using SAMS-areas (small area for market statistics), which is an older neighborhood definition, as neighborhood units like in Scarpa (2016).

[11] We use the municipal and DESO borders in 2017.

using each family as an income unit. When constructing measures of inequality and segregation, we use residents between the ages of 21 and 65 since these working-age individuals are the most interesting from a labor market perspective.

We use two different income measures: disposable income and pre-tax income. Pre-tax income includes income from all recorded sources with labor and capital incomes being the dominant components. Disposable income is pre-tax income minus taxes plus transfers.[12] Disposable income is indicative of consumption ability and is the definition of income previously used in segregation research. On the other hand, pre-tax income is indicative of earning ability and is a definition of income frequently used in inequality research.

Public redistribution introduces a wedge between pre-tax and disposable incomes. This wedge is substantial because Sweden is among the most egalitarian societies in the world with total public spending accounting for around 50% and municipal public spending accounting for around 20% of the national GDP. Municipalities and counties have fiscal autonomy; e.g., they set their local tax rates. The tax and transfer system as a whole has differential impacts on individuals depending not only on their pre-tax income but also on factors such as number of children and municipality of residence. The exact rules and policy changes during our sample period have been documented before in public finance research.[13]

Public financing of schools and pre-schools accounts for over 40% of total municipal spending. While publicly financed, the schools may be managed publicly (public schools) or privately (charter schools) since 1992. A government-funded voucher follows each pupil to the school that he or she attends, and parents can freely apply to schools for their children. About 20% of pupils attend charter schools today. Whereas public schools use proximity to home as the primary admission principle, charter schools often use queuing time as the main selection tool. Since most children attend the school closest to where they live, families often consider the school quality in a neighborhood in their residential decisions.

In many neighborhoods, most dwellings are either apartments or detached houses. About half of the population lives in each of the two housing types. While residents in detached houses generally own their homes, most apartments are rentals. However, tenant-owned cooperative apartments have increased in popularity. A large share of the apartments in Sweden today were constructed in the 1960s and 1970s as part of a government-driven construction program to provide minimum-standard homes affordable to everyone. Representatives for the landlords and tenants centrally set the rents through negotiations. These negotiations often result in rent levels that are lower than what would have prevailed in a free market. The fact that we observe long housing queues in larger cities, especially in central locations, indicates that the rent levels probably have created excess demand and low supply incentives; thus, there are substantial moving frictions. Besides rent negotiations, many other factors have favored rented homes, including more generous housing allowance rules for low-income residents, rapidly increasing housing prices on owned homes since the 1990s, and a property tax of 1% of the assessed value before 2008. However, homeowners get tax reductions of 30% of mortgage interest payments. Moreover, recent interest rates around zero might have shifted the housing cost imbalance in the opposite direction benefiting homeownership. Altogether, housing quality and costs are probably very important determinants of neighborhood choice.

### 2.2. Overall inequality and segregation and their development over time

There are several ways to quantify inequality from an income distribution. In Section 5, we use multiple measures each focusing on a limited part of the income distribution. However, it is also convenient to have a summarizing measure accounting for the entire income distribution. There are many candidates for such an overall measure, each with different pros and cons (Silber, 1999). Typically, overall measures correlate highly with each other. For our purposes, we want an overall inequality measure with an intuitive meaning that is also simple to relate to an overall measure of residential segregation. Our choice falls on the standard deviation of the logarithm of CPI-adjusted income across individuals in the municipality ($Sd_{mt}$ for municipality $m$ in year $t$).[14] Logarithms simplify relative comparisons, and the standard deviation quantifies the dispersion of a distribution in a way that is easy to relate to the mean.

The municipal standard deviation ($Sd_{mt}$) contains a between-neighborhood component ($BetweenSd_{mt}$) and a within-neighborhood component ($WithinSd_{mt}$) such that $Sd^2_{mt} = BetweenSd^2_{mt} + WithinSd^2_{mt}$.[15] The between-neighborhood component reflects income disparities across neighborhoods and is a potential measure of overall municipal segregation. If there is no inequality ($Sd_{mt} = 0$), then there cannot be any segregation ($BetweenSd_{mt} = 0$).

Previous empirical literature did not use $BetweenSd_{mt}$ as the main segregation measure. To understand the rationale, consider the case where the income distribution is stretched out without affecting the relative income ranks of the residents in the distribution. In this case, both $Sd_{mt}$ and $BetweenSd_{mt}$ increase if no residents spatially reallocate. When quantifying the residential sorting effects of inequality on segregation, one wants to eliminate the influence of this mechanical effect of $Sd_{mt}$ on $BetweenSd_{mt}$.

[12] We adjust for all taxes and transfers except consumption taxes.

[13] For instance, Blomquist and Selin (2010) and Liang (2012) provided detailed descriptions for the period before 2000, and Edmark et al. (2016) described major changes thereafter.

[14] We use the logarithm of income (SEK at the 2017 price level) plus a constant of one as the logarithm of zero is not defined.

[15] We let $BetweenSd^2_{mt} = \sum_n Residents_{nt}(\overline{Income}_{nt} - \overline{Income}_{mt})^2 / \sum_n Residents_{nt}$, where $Residents_{nt}$ is number of residents in neighborhood $n$ (in municipality $m$ in year $t$) and $\overline{Income}_{nt}$ and $\overline{Income}_{mt}$ are means of log income (across residents) in neighborhood $n$ and municipality $m$, respectively. $WithinSd_{mt}$ could be recovered from $Sd_{mt}$ and $BetweenSd_{mt}$.

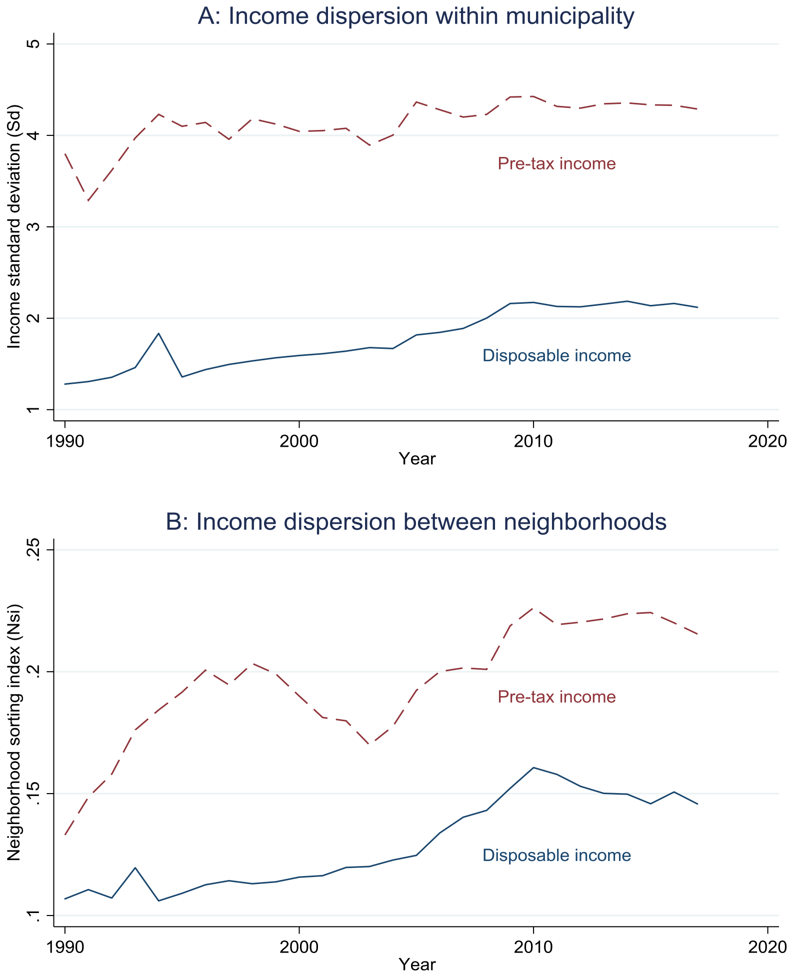


**Fig. 1.** Overall municipal inequality and segregation over time, Note: We report across-municipality yearly means (working-age population weights).

The neighborhood sorting index ($Nsi_{mt}$) is the between-neighborhood income dispersion divided by the municipal income dispersion:

$$Nsi_{mt} = \frac{BetweenSd_{mt}}{Sd_{mt}}. \quad (1)$$

This index is free from the above-mentioned mechanical effect and assumes values between zero and one.[16] Similar to inequality measures, there are several more or less correlated segregation measures each with different advantages and disadvantages (Reardon and O'Sullivan, 2004). In addition to $Nsi_{mt}$, we also use other segregation measures, each focusing on a different part of the income distribution, as we discuss in Section 5.

In Fig. 1, we plot yearly weighted means of our measures of overall municipal inequality ($Sd_{mt}$) in Panel A and segregation ($Nsi_{mt}$) in Panel B for disposable income (solid lines) and pre-tax income (dashed lines), respectively. We use municipal

[16] The standard deviation is the square root of the variance, and the between- and within-neighborhood variances sum to the total variance. It follows that *Nsi* equals the square root of the *share* of total variance that is due to between-neighborhood variance.

working-age population weights throughout the paper because we think of residents as the fundamental units experiencing inequality with potential effects on their residential choice.[17]

Because of the large Swedish tax and transfer system, $Sd_{mt}$ is much lower for disposable income than for pre-tax income. Fig. 1 shows that disposable income mean $Sd_{mt}$ increased by 66% (from 1.28 to 2.12) between 1990 and 2017; the corresponding increase in terms of pre-tax income is 13% (from 3.80 to 4.29) and less consistent over time. This pattern reflects the downsizing of public redistribution experienced by Sweden during the sample period. For segregation, we see that mean $Nsi_{mt}$ increased by 37% for disposable income (from 0.107 to 0.146) and by 62% for pre-tax income (from 0.133 to 0.215). Income inequality and residential segregation closely followed each other over time with regard to both income measures.

## 3. Empirical strategy

### 3.1. Starting from a first-difference design

Fig. A1 in the Appendix shows a positive relationship between income inequality and residential segregation across our 290 municipalities. However, municipalities differ regarding a range of observable and unobservable factors correlated with municipal inequality and segregation, e.g., socio-demographic composition, labor market condition, and topography. The policymakers cannot affect many of those factors (e.g., topography). We are interested in the effects of changing policy-relevant determinants of income inequality, and the factors that policymakers cannot affect are considered to be confounders.

Following previous research, we first address cross-sectional confounders by using a first-difference design exploiting within-municipality variation over time. If inequality affects segregation, ceteris paribus, municipalities facing inequality changes over time will also experience segregation changes. Upon comparing municipalities with different inequality changes, those facing greater inequality changes should also experience greater segregation changes. Confounders varying across municipalities but remaining constant within each municipality over time do not affect municipal changes in inequality and segregation. Hence, municipality-fixed effects have been differenced away.

Fig. A2 in the Appendix shows scatter plots of municipal changes in segregation against inequality between 1990 and 2017. The plots reveal positive correlations between inequality and segregation changes across municipalities.

It is possible to construct municipal changes spanning shorter time intervals than the entire sample period; e.g., we can construct 27 one-year changes (1990–1991, 1992–1993, ..., 2016–2017) for each municipality. We let $\Delta Sd_{mt} = Sd_{m,t+\Delta t} - Sd_{mt}$ and $\Delta Nsi_{mt} = Nsi_{m,\ t+\Delta t} - Nsi_{mt}$ denote changes in overall inequality and segregation for municipality $m$ between base year $t$ and end year $t + \Delta t$ where $\Delta t$ is difference length.

We pool changes with different base years, when possible, to fully utilize our municipal panel. Thus, each combination of municipality and base year forms an observation. However, changes from different base years are likely not fully comparable with each other (even for the same municipality). Underlying national factors changing over time but common to all municipalities at a certain point in time could generate differential segregation trends over time even absent inequality change. We address time-varying confounders correlated with both inequality and segregation changes using base-year dummies in the estimation.

Letting $In_{mt}$ and $Seg_{mt}$ denote different possible inequality and segregation variables, respectively (only $Sd_{mt}$ and $Nsi_{mt}$ have been discussed so far), we first estimate the following first-difference equation by least squares:

$$\Delta Seg_{mt} = \beta \Delta In_{mt} + \sigma_t + \varepsilon_{mt}. \tag{2}$$

The coefficient $\beta$ is the main parameter of interest. Time-fixed effects are captured by $\sigma_t$ (base-year dummies), and $\varepsilon_{mt}$ represents idiosyncratic errors. Throughout this paper, we weight regressions by the municipal working-age population in the base year and cluster standard errors at the municipality level. This standard first-difference design exploits the combined municipality-by-year variation in inequality and segregation.

In Fig. 2, we explore the dynamics over different time horizons by estimating Eq. (2) and letting the difference length vary between 1 and 27 years, and we report point estimates (dots) and 95% confidence intervals (bars). The point estimates are all positive. While the point estimate for disposable income is negatively dependent on the difference length, confidence intervals are relatively wide when the difference length is long.[18]

### 3.2. Accounting for confounding trends

Confounders could still drive correlations between municipal *changes* in inequality and segregation. For instance, inequality and segregation could have increased primarily in high-population municipalities because of agglomeration economies. We account for confounding heterogeneous segregation trends between municipalities by adding control variables to

[17] The patterns and results in this paper are robust to giving each municipality the same weight.

[18] Reallocation frictions may cause residential sorting effects to vary with the time horizon. Moving involves fixed costs, and it takes time to update knowledge on neighborhood-level information. Thus, residents may not immediately respond to changing conditions; longer-run residential sorting effects could therefore be larger. However, we cannot interpret the patterns in Figure 2 in support of (or against) this hypothesis, since the impact of reverse causation and mechanical effects likely varies with the time horizon.

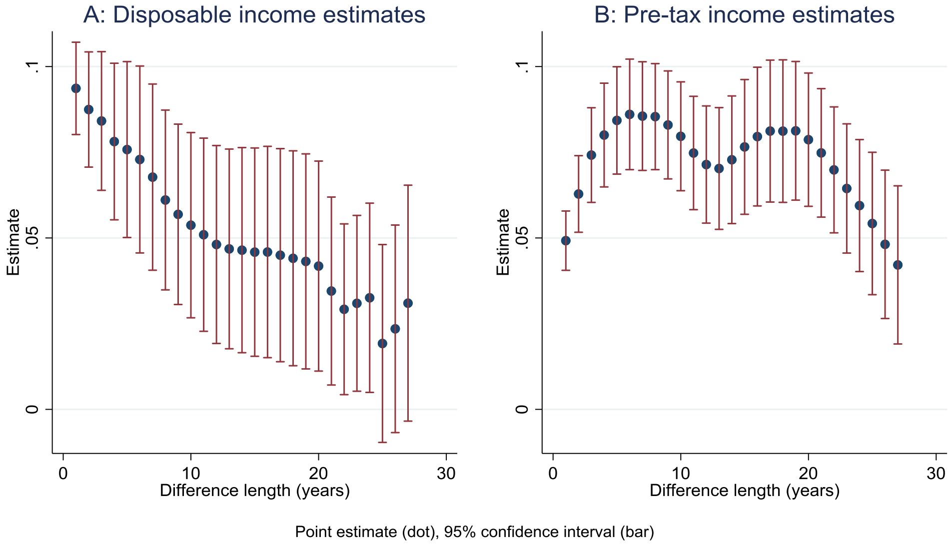


**Fig. 2.** Regressions of inequality change on segregation change by difference length, Note: We run (weighted) regressions of $Nsi_{m,t+\Delta t} - Nsi_{mt}$ on $Sd_{m,t+\Delta t} - Sd_{mt}$, $\Delta t = 1, \ldots, 27$.

Eq. (2). The covariates that we add are described in detail below consecutively, and the following equation describes our main regression specification:

$$\Delta Seg_{mt} = \beta \Delta In_{mt} + \gamma_1 \Delta \overline{In}_{mt} + \boldsymbol{\gamma}_2 \boldsymbol{z}_{mt} + \gamma_3 \Delta In_{mt}^{stay} + \sigma_t + \varepsilon_{mt}. \quad (3)$$

When facing an inequality change, it may take some time for residents to spatially reallocate. This justifies using a longer difference length. However, there is a political impatience in terms of quickly achieving effects; thus, policymakers are also interested in shorter-run effects. Moreover, the number of first-differences increases as we decrease the difference length, which improves statistical precision. When we report regression estimates, we strike a balance between these concerns by using five-year changes.[19] Thus, there are five-year changes (1990–1995, 1991–1996, ..., 2012–2017) from 23 base years (1990, 1991, ..., 2012). Table A1 in the Appendix provides summary statistics for our estimation sample.

As the dependent and main independent variables of interest in Eq. (3), we first estimate a specification using disposable income $\Delta Nsi_{mt}$ and $\Delta Sd_{mt}$. There is then a second specification using pre-tax income $\Delta Nsi_{mt}$ and $\Delta Sd_{mt}$. In the first specification, when estimating the influence of disposable income $Sd_{mt}$, we control for the influence of pre-tax income $Sd_{mt}$, and vice versa in the second specification. For this purpose, we include the covariate $\Delta \overline{In}_{mt}$, which is the inequality change for the complementary income measure. Thus, when $\Delta In_{mt}$ equals disposable income $\Delta Sd_{mt}$, $\Delta \overline{In}_{mt}$ equals pre-tax income $\Delta Sd_{mt}$, and vice versa.[20]

Previous literature focused on inequality and segregation in terms of disposable income which is pre-tax income adjusted for public redistribution. To evaluate the role of public redistribution, one needs to account for the correlation between disposable income and pre-tax income. Otherwise, the estimated relationship between disposable income inequality and segregation may simply reflect the corresponding relationship for pre-tax income, which in turn may be driven by determinants of pre-tax incomes. Such determinants include individual characteristics such as age, education, and innate ability as well as structural factors affecting local labor market conditions. These factors may have direct effects on residential preferences and segregation. Given that we control for changes in pre-tax income inequality, we shut down the channel through which its determinants correlate with changes in disposable income inequality. The remaining variation derives entirely from the municipality-by-year variation in the distribution of disposable incomes due to changes in the tax and transfer system.

Changes in the tax and transfer system have different effects on residents across municipalities. First, residents have to pay local taxes consisting of county-specific and municipality-specific taxes. These taxes have changed differentially across municipalities over time. Second, taxes and transfers set by the central government have different effects on residents depending on pre-tax income as well as other individual characteristics, e.g., the number of children. Since the residential composition differs across municipalities (and over time), the same rules (or rule changes) do not affect the municipalities

[19] That is to say, we use $\Delta Var_{mt} = Var_{m,t+5} - Var_{mt}$ for different variables $Var$.

[20] Our results are insensitive to controlling for additional parameters of the distribution of the complementary income measure, e.g., the poverty and affluence rate variables in Section 5.

in the same way. Importantly, these rules interact with local taxes creating additional variation.[21] In public finance research, the tax and transfer system or its change is regularly assumed to be an exogenous determinant of an individual's disposable income (see, e.g., the critical review by Saez et al., 2012). The differential impact of the tax and transfer system in Sweden has been documented and used many times before (e.g., Blomquist and Selin, 2010).

Our identification of disposable income effects relies on only variation in public redistribution across municipalities and over time, but pre-tax income effects may be driven by a host of factors that determine the pre-tax income distribution. We thus control for several municipality-specific covariates in the vector $\boldsymbol{z}_{mt}$. First, $\boldsymbol{z}_{mt}$ includes socio-demographic base-year variables related to education, country of birth, and age. The covariates consist of share that did not graduate high school, share with a university degree, share born in Europe but outside Sweden, share born outside Europe, share of young residents/children (aged 20 or below), share of old residents (aged 66 or above), and shares in eight age groups (five-year intervals). Second, $\boldsymbol{z}_{mt}$ contains base-year segregation ($Seg_{mt}$) and inequality ($In_{mt}$) to account for mean-reversion patterns. Such patterns would exist, e.g., if there is a tendency for segregation to revert to a long-run equilibrium after having been high because of transitory factors. Third, to control for general underlying urbanization processes, population and population change divided by base-year population are included as covariates in $\boldsymbol{z}_{mt}$. Fourth, our data allow us to construct square meter housing space per person and its change over time. These variables are also included in $\boldsymbol{z}_{mt}$ to account for housing market conditions. Ideally, we would also control for school quality if such data were available.

Variables accounting for *base-year* education, country of birth, and age compositions in $\boldsymbol{z}_{mt}$ are determined prior to inequality and segregation changes due to subsequent policy. However, *changes* in those compositions are *not* included in $\boldsymbol{z}_{mt}$. Public policies designed to change inequality may achieve this by changing the municipal socio-demographic composition. Thus, such changes represent mechanisms of interest. To explore these mechanisms, we provide additional estimates using specifications that control for changes in education, country-of-birth, and age compositions (in addition to the basic covariates in Eq. (3)). By comparing estimates with and without these additional covariates, we can identify the importance of these inequality determinants for fighting segregation.

### 3.3. Accounting for reverse causation and mechanical effects

Even with all covariates in Eq. (3) except $\Delta In_{mt}^{stay}$, a conditional correlation between inequality and segregation changes may not reflect residential sorting effects of inequality on segregation arising from how residential choices change as incomes change (Tiebout, 1956; Schelling, 1969). Existing residential segregation by income in the base year due to past residential choices can lead to future changes in inequality and segregation for multiple reasons unrelated to new residential choices.[22] First, neighborhood effects may reinforce income inequality generating reverse causation. Second, changes in economic conditions can have mechanical effects on inequality and segregation. Over (a potentially long) time, the impact of reverse causation and mechanical effects diminishes as residents overcome reallocation frictions. However, the residential sorting effect of inequality on segregation strengthens with time.

In order to evaluate whether public policies reducing inequality can affect residential sorting and segregation, we rule out reverse causation and mechanical effects using a novel strategy. We exploit the fact that in-moving residents from other municipalities are not part of existing residential patterns in the destination municipality that may drive inequality and segregation changes. However, they do change the population income composition and thus inequality in the destination municipality. Any effects on segregation must involve active residential choices including where the in-movers decide to reside. In-movers are a group that we know have overcome reallocation frictions. They may also cause subsequent neighborhood reallocation of other residents in the destination municipality.

We implement our strategy accounting for reverse causation and mechanical effects by controlling for the part of $\Delta In_{mt}$ that is due to "staying" residents who did *not* move in from other municipalities between the base and end years. In Eq. (3), we include the following synthetic inequality covariate:

$$\Delta In_{mt}^{stay} = In_{m,t+5}^{stay} - In_{mt}. \tag{4}$$

All residents used for calculating $In_{m,t+5}$ except those who moved in between years $t$ and $t+5$ are used to calculate $In_{m,t+5}^{stay}$.

With the synthetic inequality covariate in Eq. (4), only variation in inequality change caused by the income distribution of in-movers is used for identifying $\beta$ in Eq. (3). To see this, note that $\beta\Delta In_{mt} + \gamma_3 \Delta In_{mt}^{stay} = \beta(\Delta In_{mt} - \Delta In_{mt}^{stay}) + (\gamma_3 + \beta)\Delta In_{mt}^{stay}$. Identification of $\beta$ relies on variation in $\Delta In_{mt} - \Delta In_{mt}^{stay}$. The variables $\Delta In_{mt}$ and $\Delta In_{mt}^{stay}$ assume different values only when in-movers have a different income distribution than stayers ($In_{m,t+5} \neq In_{m,t+5}^{stay}$); varying income distributions of in-movers provide the identifying variation.

On average, 15.6% of the municipal population in year $t+5$ consists of residents that moved in after year $t$. Hence, there is scope for in-movers to cause a substantial external shock to the population income composition in the destination municipality. We rely on the municipality-by-year variation in this shock. To study the amount of variation in this shock, Table 1 reports the means and standard deviations for our overall inequality variable $\Delta Sd_{mt}$ and its two additive components

[21] For instance, capital losses are deductible also toward local taxes.

[22] To some degree, controlling for base-year segregation in $\boldsymbol{z}_{mt}$ accounts for this issue. However, the correct functional form is likely complicated and unlikely linear in one specific measure of base-year segregation.

**Table 1**
Variation in five-year inequality changes due to stayers and in-movers.

| | (1) Disposable income | (2) | (3) Pre-tax income | (4) |
|---|---|---|---|---|
| | Mean | Std dev. | Mean | Std dev. |
| $\Delta Sd_{mt}$ (total) | 0.144 | 0.203 | 0.114 | 0.268 |
| $\Delta Sd^{stay}_{mt}$ (stayers) | 0.187 | 0.219 | 0.145 | 0.266 |
| $\Delta Sd_{mt} - \Delta Sd^{stay}_{mt}$ (movers) | −0.043 | 0.068 | −0.031 | 0.106 |

Note: We use working-age population weights.


**Fig. 3.** Share of Swedish population that moved between municipalities the last five years.

($\Delta Sd_{mt} - \Delta Sd^{stay}_{mt}$) and $\Delta Sd^{stay}_{mt}$. The standard deviations are smaller for ($\Delta Sd_{mt} - \Delta Sd^{stay}_{mt}$) than for $\Delta Sd^{stay}_{mt}$, but only by a factor of two to three (0.068 vs. 0.219 in column 2, and 0.106 vs. 0.266 in column 4). Hence, there is substantial variation in inequality changes due to in-movers.[23]

We now turn our attention to the in-movers. Fig. 3 shows the prevalence of individuals who moved between municipalities in the last five years over time. We see that the number of movers increased from representing 14.0% of the population in 1995 to 16.3% in 2017.

Table 2 presents regression estimates of the share of in-movers between years $t$ and $t+5$ (using the population in year $t$ as the denominator) on several variables describing socio-demographic characteristics in the destination municipality in year $t$. Column (1) shows that migration streams go toward populous municipalities. However, once also including population change as an independent variable in column (2), the correlation between share of in-movers and population disappears. There is a near one-to-one positive relationship between share of in-movers and population change (as indicated by the estimate of 0.886) since in-movers mechanically also increase municipal population. Column (3) shows that movers generally migrated to municipalities with lower shares of residents without a high-school degree. Estimates for the other covariates are not statistically significant.

Inter-municipal migration might affect income inequality between municipalities (i.e., income segregation between municipalities). Fig. A3 in the Appendix shows how the between-municipality sorting index developed over time. This index is constructed using the *Nsi* measure in Eq. (1) treating Sweden as the main unit and the municipalities as the subunits. We see that inequality between municipalities has increased since 1990.

While controlling for several migration determinants, there are still determinants that we do not control for that do affect the income distribution of the in-movers. For instance, a municipality might stimulate the local job market for high-skill individuals and thus attract affluent individuals from other municipalities. Some of these determinants may also affect stayers' neighborhood choices even if the income distribution had been held constant. The jobs created may be located in the city center and increase spatial sorting by income between the center and the outskirts. Thus, such determinants might have direct effects on segregation and therefore confound the inequality effect. We are interested in whether public policies targeting inequality subsequently affect residential segregation, and thus we do not want to eliminate all policy variation. However, the direct effects of public policies (and other omitted variables) on segregation represent potential threats to the identification of inequality effects.

[23] Ultimately, regression results will reveal whether there is an issue with statistical power.

**Table 2**
Demographic determinants of the share of in-movers.

| Dependent variable: Share of in-movers | (1) | (2) | (3) |
|---|---|---|---|
| Population (million) | 0.0590** | 0.00762 | −0.0324 |
| | (0.0138) | (0.0172) | (0.0576) |
| Population change (divided by base level) | | 0.886** | 0.587** |
| | | (0.0956) | (0.0969) |
| Education: share no high-school degree | | | −0.167* |
| | | | (0.0707) |
| Education: share university degree | | | 0.0181 |
| | | | (0.0267) |
| Born: share Europe but outside Sweden | | | 0.129 |
| | | | (0.0983) |
| Born: share outside Europe | | | 0.0960 |
| | | | (0.151) |
| Age: share < 21 years old | | | −0.397 |
| | | | (0.507) |
| Age: share > 65 years old | | | −0.361 |
| | | | (0.200) |
| Year dummies | Yes | Yes | Yes |

Notes: There are 6670 observations (290 municipalities and 23 base years 1990–2012). Share of in-movers and population change refers to changes between years $t$ and $t+5$ divided by the population in year $t$. Other independent variables refer to values in the base year $t$. We weight regressions by the working-age population in the base year, and we report standard errors clustered at the municipality level in parentheses.
* $p < 0.05$.
** $p < 0.01$.

**Table 3**
The influence of overall inequality on segregation.

| Dependent variable: $\Delta Nsi$ | (1) | (2) | (3) |
|---|---|---|---|
| Independent variable: $\Delta Sd$ | A: Disposable income estimates | | |
| No stayer control | 0.0758** | 0.0726** | 0.0619** |
| | (0.0131) | (0.0137) | (0.0136) |
| With stayer control ($\Delta Sd^{stay}$) | 0.0301* | 0.0224 | −0.00673 |
| | (0.0152) | (0.0176) | (0.0325) |
| | B: Pre-tax income estimates | | |
| No stayer control | 0.0843** | 0.0872** | 0.0921** |
| | (0.00799) | (0.0106) | (0.00905) |
| With stayer control ($\Delta Sd^{stay}$) | 0.0777** | 0.0802** | 0.100** |
| | (0.0118) | (0.0144) | (0.0168) |
| Base-year dummies | Yes | Yes | Yes |
| Inequality complement ($\Delta\overline{Sd}$) | No | Yes | Yes |
| Other covariates ($\boldsymbol{z}$) | No | No | Yes |

Notes: There are 6670 observations of five-year changes (290 municipalities and 23 base years 1990–2012). Other covariates ($\boldsymbol{z}_{mt}$) include share that did not graduate high school, share with a university degree, share born in Europe but outside Sweden, share born outside Europe, share of young residents (aged 20 or below), share of old residents (aged 66 or above), shares in eight age groups (five-year intervals), population and population change divided by base-year population, housing space per person and its change, and base-year segregation ($Nsi_{mt}$) and inequality ($Sd_{mt}$). We weight regressions by the working-age population in the base year, and we report standard errors clustered at the municipality level in parentheses.
* $p < 0.05$.
** $p < 0.01$.

## 4. Main results

### 4.1. Estimates for overall inequality and segregation

Starting with overall inequality and segregation, we analyze the relationship between $Sd_{mt}$ (standard deviation of log income) and $Nsi_{mt}$ (neighborhood sorting index) in Table 3. Specifically, following Eq. (3), we report estimates of $\beta$ from first-difference regressions of five-year changes in segregation ($\Delta Sd_{mt}$) on inequality ($\Delta Nsi_{mt}$) for disposable income (Panel A) and pre-tax income (Panel B). In column (1), we include only year dummies as covariates. In column (2), we also control for the complementary measure of inequality change ($\Delta\overline{Sd}_{mt}$, constructed using pre-tax income in Panel A and disposable income in Panel B). In column (3), we add mostly base-year covariates ($\boldsymbol{z}_{mt}$). In the second rows of estimates in each panel, we rule out reverse causation and mechanical effects by including the stayer control ($\Delta Sd_{mt}^{stay}$). Identification of the residential sorting effect of inequality on segregation then fully relies on how in-moving residents from other municipalities change inequality in the destination municipality.

Panel A of Table 3 shows positive point estimates of the slope coefficient (0.0619 to 0.0758) that are statistically significant at the one percent level when omitting the stayer control. Controlling for changes in pre-tax income inequality in column (2) does not substantially affect the point estimate or standard errors. In doing so, identification of disposable income effects also fully relies on municipality-by-year variation due to changes in the tax and transfer system.

After accounting for reverse causation and mechanical effects using the stayer control in Panel A, the point estimates decrease and become statistically insignificant in columns (2) and (3). Thus, the positive relationship between changes in inequality and segregation without the stayer control might exist because segregation leads to inequality through neighborhood effects. Alternatively, tax and transfer system changes mechanically affected residents in low- and high-income neighborhoods differently. Such changes could strengthen both existing segregation and inequality patterns leading to the estimated positive relationship.[24]

Our results show that changes in disposable income inequality due to in-moving residents did *not* lead to residential sorting across neighborhoods in a way that had a greater impact on residential segregation. Thus, we can conclude that public redistribution that changed municipal income dispersion did not result in active residential choices such that between-neighborhood dispersion was affected. In column (3), the estimated residential sorting effect of disposable income inequality due to public redistribution is -0.00673. The standard errors are larger with the stayer control than without it. We can rule out greater positive effects above 0.0570 from the 95% confidence interval ($-0.00673 \pm 1.96 \times 0.0325$).

In Panel B of Table 3, the pre-tax income point estimates are all positive and statistically significant at the one percent level. We obtain a point estimate of 0.100 when we add all covariates (column 3) including the stayer control. This estimate shows that the inequality changes generated by changes in the population income composition due to in-moving residents resulted in subsequent residential sorting across neighborhoods. As municipal income dispersion increases, between-neighborhood income dispersion will proportionally increase even more.

We can relate the pre-tax income point estimates to the summary statistics in Table A1 in the Appendix (where mean $\Delta Sd_{mt} = 0.114$ and mean $\Delta Nsi_{mt} = 0.011$ for pre-tax income). The estimate of 0.100 translates into a (sample) mean five-year effect of 0.011 ($=0.100 \times 0.114$), which is equal to the mean five-year segregation change. Hence, mean inequality growth can account for the *entire* mean segregation rise during the sample period. This result also means that if inequality hypothetically had not increased (i.e., stayed constant at its level in 1990), segregation would not have changed.[25]

Our results indicate that the scope to which public redistribution affects residential sorting across neighborhoods and thereby segregation seems limited. Instead, policymakers who want to prevent segregation due to residential sorting by reducing inequality should focus on equalizing pre-tax incomes rather than disposable incomes. Since unequal pre-tax incomes matter conditional on disposable income inequality, unequal earning capacities matter even if consumption capacities are equalized via public redistribution. Policymakers could attempt to equalize “skills” that matter in the labor market.[26] In the next subsection, we analyze the role of socio-demographic determinants of pre-tax incomes.

As a sensitivity test, Table A2 in the Appendix presents estimates corresponding to those in Table 3, but there we treat each family (instead of each individual) as an income unit when constructing inequality and segregation measures. The pattern of results is very similar to that in Table 3.

To address potential bias due to remaining confounding trends, we include lagged $\Delta Sd_{mt}$ ($= Sd_{mt} - Sd_{m,t-5}$) as an additional covariate. This variable can be regarded as a placebo that should not affect current segregation change if one believes that most effects of inequality on segregation realize within five years. Even in the case there are longer-run effects, if including lagged $\Delta Sd_{mt}$ significantly changes the estimate of the effect of $\Delta Sd_{mt}$, then we cannot reasonably claim that this estimate is unconfounded by other trends. We also elaborate with controlling for the spatial lag of $\Delta Sd_{mt}$ that is defined as the mean of $\Delta Sd_{mt}$ across all municipalities except $m$ in the same county (there are 21 counties in Sweden). The purpose is to account for spatial income clustering and spillover effects of inequality in one municipality on its neighboring municipalities. We report the results from these sensitivity tests in Table 4. We find that the main inequality effect (of $\Delta Sd_{mt}$) is robust to adding lagged $\Delta Sd_{mt}$ and/or the spatial lag of $\Delta Sd_{mt}$ as covariates.[27] Moreover, the point estimates for lagged $\Delta Sd_{mt}$ are small and not statistically significant (never at the 5% level). We do, however, find some spatial dependence and statistically significant point estimates for the spatial lag of $\Delta Sd_{mt}$.

[24] The existence of a positive correlation due to reverse causation and mechanical effects, but not due to residential sorting, is consistent what we observed in Fig. 2. If there are no residential sorting effects, then the impact of reverse causation and mechanical effects diminishes as the time horizon becomes longer, which decreases the point estimate.

[25] This does not mean that inequality change is the only determinant of segregation change. Explanatory power is not 100% (R-squared is not equal to one).

[26] Moreover, municipalities could try to change the skill distribution via migration; in other words, they could make themselves more attractive for mid-skill residents and less attractive for low- and high-skill residents. However, at least regarding internal migration within a country, this is typically a zero-sum game among the municipalities and the effects cannot be scaled up to the national level.

[27] Unreported results also show robustness to adding lagged $\Delta Nsi_{mt}$ and the spatial lag of $\Delta Nsi_{mt}$ as covariates.

**Table 4**
Sensitivity test: Including the lag and spatial lag of inequality changes as covariates.

| Dependent variable: $\Delta Nsi$ | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| | A: Disposable income estimates | | | |
| $\Delta Sd$ | 0.00242 | −0.00486 | 0.0372 | 0.0270 |
| | (0.0291) | (0.0285) | (0.0272) | (0.0263) |
| Lagged $\Delta Sd$ | | 0.0118 | | 0.0181* |
| | | (0.00863) | | (0.00797) |
| Spatial lag of $\Delta Sd$ | | | −0.0768** | −0.0791** |
| | | | (0.0120) | (0.0121) |
| | B: Pre-tax income estimates | | | |
| $\Delta Sd$ | 0.130** | 0.130** | 0.132** | 0.132** |
| | (0.0171) | (0.0170) | (0.0171) | (0.0171) |
| Lagged $\Delta Sd$ | | −0.000304 | | 0.0000605 |
| | | (0.00747) | | (0.00762) |
| Spatial lag of $\Delta Sd$ | | | −0.0217* | −0.0217* |
| | | | (0.0106) | (0.0105) |

Notes: There are 5202 observations of five-year changes (289 municipalities and 18 base years 1995–2012, Gotland municipality which is also an own county is not included). All regressions include the stayer control ($\Delta Sd^{stay}_{mt}$), base-year dummies, the inequality complement ($\Delta \overline{Sd}_{mt}$), and other covariates ($\boldsymbol{z}_{mt}$). See the notes of Table 3 for more details. Whereas $\Delta Sd_{mt} = Sd_{m,t+5} - Sd_{mt}$, lagged $\Delta Sd_{mt} = Sd_{mt} - Sd_{m,t-5}$, and spatial lag of $\Delta Sd_{mt}$ is the (working-age population weighted) mean of $\Delta Sd_{mt}$ across all municipalities except $m$ in the same county. We weight regressions by the working-age population in the base year, and we report standard errors clustered at the municipality level in parentheses.
* $p < 0.05$.
** $p < 0.01$.

**Table 5**
Effects of inequality on segregation accounting for socioeconomic changes.

| Dependent variable: $\Delta Nsi$ | (1) | (2) | (3) | (4) | (5) |
|---|---|---|---|---|---|
| | A: Disposable income estimates | | | | |
| $\Delta Sd$ | −0.00673 | −0.0161 | −0.0104 | 0.00568 | −0.00218 |
| | (0.0325) | (0.0372) | (0.0321) | (0.0390) | (0.0411) |
| | B: Pre-tax income estimates | | | | |
| $\Delta Sd$ | 0.100** | 0.0258 | 0.0923** | 0.111** | 0.0440** |
| | (0.0168) | (0.0176) | (0.0152) | (0.0187) | (0.0168) |
| Education changes | No | Yes | No | No | Yes |
| Country-of-birth changes | No | No | Yes | No | Yes |
| Age changes | No | No | No | Yes | Yes |

Notes: There are 6670 observations of five-year changes (290 municipalities and 23 base years 1990–2012). All regressions include the stayer control ($\Delta Sd^{stay}_{mt}$), base-year dummies, the inequality complement ($\Delta \overline{Sd}_{mt}$), and other basic covariates ($\boldsymbol{z}_{mt}$). See the notes of Table 3 for more details. Education changes include changes in share that did not graduate high school and share with a university degree. Country-of-birth changes include changes in share born in Europe but outside Sweden and share born outside Europe. Age changes include changes in share of young residents (aged 20 or below), share of old residents (aged 66 or above), and shares in eight age groups (five-year intervals). We weight regressions by the working-age population in the base year, and we report standard errors clustered at the municipality level in parentheses.
* $p < 0.05$.
** $p < 0.01$.

### 4.2. Exploring mechanisms

Pre-tax income correlates with socio-demographic characteristics, and thus policymakers could influence income inequality by changing the population composition along socio-demographic dimensions. In Table 5, we explore how some aspects of this composition play a role by controlling for changes in education, country-of-birth, and age compositions. These variables are five-year changes of the base-year covariates. We start from the full regression specification in Eq. (3) with all basic covariates (column 1) and then add either municipal share changes in different education groups (column 2), country-of-birth groups (column 3), or age groups (column 4). In column (5), we include all basic and additional covariates.

Panel A of Table 5 shows that the additional covariates do not dramatically affect the disposable income estimates. However, Panel B of Table 5 shows that the pre-tax income point estimate of 0.100 (column 1) is sensitive to controlling for changes in the education composition in column (2); it decreases to 0.0258 (by 74%) and is no longer statistically significant. Hence, much of the residential sorting effects across neighborhoods disappear once controlling for how in-movers change

**Table 6**
Effects of inequality on segregation across housing types.

| Dependent variable: $\Delta Nsi$ | (1) Apartments | (2) Detached houses | (3) All dwellings |
|---|---|---|---|
| | A: Disposable income estimates | | |
| $\Delta Sd$ | −0.0515 | −0.0107 | −0.00673 |
| | (0.0385) | (0.0116) | (0.0325) |
| | B: Pre-tax income estimates | | |
| $\Delta Sd$ | 0.103** | 0.00646 | 0.100** |
| | (0.0229) | (0.00828) | (0.0168) |

Notes: There are 6670 observations of five-year changes (290 municipalities and 23 base years 1990–2012). All regressions include the stayer control ($\Delta Sd_{mt}^{stay}$), base-year dummies, the inequality complement ($\Delta \overline{Sd}_{mt}$), and other basic covariates ($\boldsymbol{z}_{mt}$). See the notes of Table 3 for more details. We weight regressions by the working-age population in the base year, and we report standard errors clustered at the municipality level in parentheses.
* $p < 0.05$.
** $p < 0.01$.

the education composition. Therefore, the education composition is the main driver of the influence of pre-tax income inequality on segregation due to residential sorting. This finding strongly suggests that policies equalizing education levels, and thereby skill levels, are effective in terms of fighting segregation. However, controlling for changes in the country-of-birth composition in column (3) has small effects on the point estimate (which moves from 0.100 to 0.0923). Hence, the relationship we find is not driven by residential sorting patterns of foreign-born residents.

In addition to being relevant to policy, our results are useful for understanding residential sorting mechanisms. We *cannot* establish that unequal disposable incomes reflecting unequal abilities to pay for housing quality and public goods (Tiebout, 1956) led to residential sorting in the form of between-neighborhood dispersion in disposable incomes. On the other hand, unequal pre-tax incomes reflecting unequal earning abilities led to residential sorting and segregation. This pattern could be rationalized by people being attracted to neighborhoods with others similar to themselves in terms of skill levels or factors determining skill levels. (Schelling, 1969). In particular, residential sorting depended on education levels. Higher educated individuals with higher income levels might value certain types of housing forms (e.g., detached houses) or public goods (e.g., better schools) more than others with similar consumption abilities. Moreover, they might prefer to live and interact with similar-minded (and avoid others) or care more about the neighborhood of residence as a status marker.

To explore whether residents consider housing types in their neighborhood choices, Table 6 separately analyzes inequality effects on segregation across neighborhoods for apartments and detached houses. For disposable income, we do not find any statistically significant effects. For pre-tax income, we find an effect of 0.103 (column 1) that is statistically significant when it comes to apartments. Thus, inequality increases segregation due to residential sorting across apartments in different neighborhoods. However, the point estimate for detached houses is not statistically significant (column 2). The total effect (estimated to be 0.100 in column 3) is a weighted average of the effects on segregation across apartments in different neighborhoods (column 1), segregation across detached houses in different neighborhoods (column 2), and segregation across neighborhoods with different compositions of apartments and detached houses. Finding similar total and apartment effects but no detached house effect implies that an important part of the total effect must be due to inequality leading to segregation across neighborhoods with different housing types.

## 5. The tails of the income distribution

### *5.1. Inequality and segregation along the tails of the income distribution*

Different measures of income inequality and residential segregation do not weight different parts of the income distribution in the same way.[28] Our detailed data allow us to operationalize inequality and segregation along any quantile of the income distribution in a more precise manner than the overall measures discussed previously. Fig. 4 shows kernel density fits of the national income distributions in 1990 and 2017. To adjust for growth and enable comparability over time, we display the x-axis in terms of relative income as a proportion of the median income for each year.[29] The most striking change over time is that the share of residents with income levels around the median in the middle of the income distribution has decreased.

For each distribution in Fig. 4, we mark *year-specific* first- and ninth-decile cutoffs with vertical lines. We also mark the mean of (midpoint between) the two year-specific first- and ninth-decile cutoffs, respectively, on the x-axis. Each of these proportions is a fixed constant across the two years and represents a *normalized* across-year national decile cutoff.[30]

[28] For instance, the standard deviation of income gives top incomes higher weight than the standard deviation of the logarithm of income.
[29] Hence, median income assumes a value of one on the x-axis.
[30] Such decile cutoffs almost correspond to decile cutoffs of the income distribution for the pooled sample of individuals from the two years.

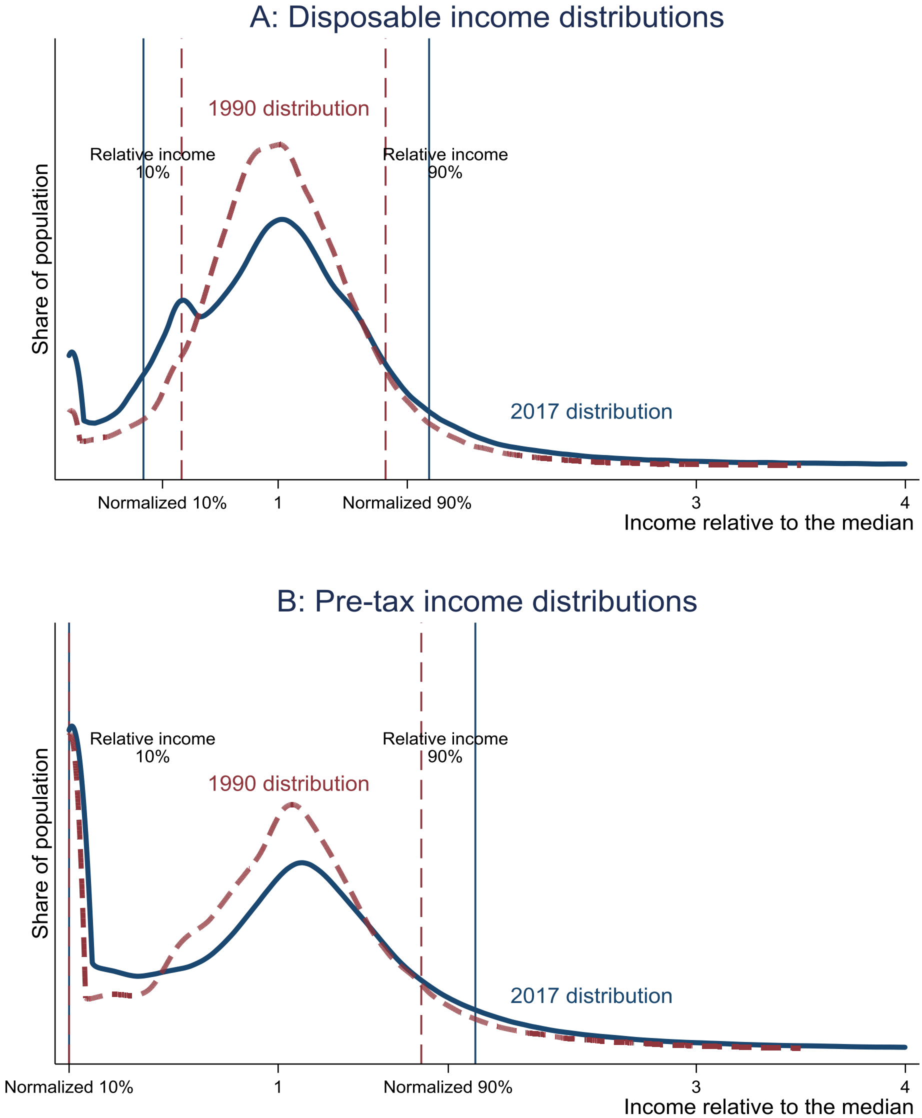


**Fig. 4.** Kernel fits of the national income distributions in 1990 and 2017.

Each of the income distributions in Fig. 4 has a peak around one as well as a lower and an upper tail. Starting with the upper tails, we see that the year-specific top-decile (9th decile) cutoffs increased implying that high-income residents have become relatively richer. In this sense, the upper tails have become *longer* (outstretched horizontally). Moreover, above the normalized top-decile cutoff, the densities have increased meaning that there are more rich residents in 2017 than in 1990. In this sense, the upper tails have become *thicker* (uplifted vertically).[31] Moving to the bottom-decile (1st decile) cutoffs, we can similarly conclude that low-income residents have become poorer (longer tails) and more numerous (thicker tails). We can construct simple and intuitive inequality measures along different decile cutoffs.

[31] For continuous distributions, tail thickness and length typically correlate, but not perfectly. The tails could primarily become longer without getting thicker, and vice versa.

Each municipality has its own income distribution that varies over time. To measure the thickness of the tails of the *municipal* income distribution, we construct municipal poverty (affluence) rates varying across years. We first express each individual's income relative to the year-specific *municipal* median. The poverty (affluence) rates are defined as the municipal shares of residents with relative incomes below (above) normalized across-year *national* decile cutoffs (such cutoffs were illustrated in Fig. 4). These normalized national cutoffs enable meaningful comparisons of poverty and affluence rates across municipalities and years. For the lower tail, we construct $Share^d_{mt}$ for deciles $d = 1, 2, 3, 4$ as the shares of poor residents with relative income *below* the 1st to 4th normalized national decile cutoffs. Similarly, for the upper tail, we construct $Share^d_{mt}$ for $d = 6, 7, 8, 9$ as the shares of rich residents *above* the 6th to 9th normalized national decile cutoffs.[32]

To measure the length of the tails of the municipal income distribution, we construct relative income measures $Ratio^d_{mt}$ as the municipal incomes of poor (rich) residents at different municipal income decile cutoffs for $d = 1, 2, 3, 4, 6, 7, 8, 9$ divided by the municipal median income. As the lower tail of the income distribution becomes longer, $Ratio^d_{mt}$ for $d = 1, 2, 3, 4$ *decreases*. Thus, these variables measure the "inverse" of lower-tail length. The opposite applies to the upper tail; as the tail becomes longer, $Ratio^d_{mt}$ for $d = 6, 7, 8, 9$ increases, and these variables measure upper-tail length.

With regard to binary groups, such as poor and non-poor (or rich and non-rich), the dissimilarity index ($Di_{mt}$) is an established measure of the spatial concentration of similar-typed residents in certain subunits within an area. Here, we let $Group_{nt}$ denote the number of poor and $\overline{Group}_{nt}$ denote the number of non-poor residents in neighborhood $n$ (locating in municipality $m$) in year $t$. Thus, $Group_{mt} = \sum_n Group_{nt}$ and $\overline{Group}_{mt} = \sum_n \overline{Group}_{nt}$ are the numbers of poor and non-poor residents in municipality $m$ in year $t$, respectively. Now:

$$Di_{mt} = 0.5 \sum_n \left| \frac{Group_{nt}}{Group_{mt}} - \frac{\overline{Group}_{nt}}{\overline{Group}_{mt}} \right|. \tag{5}$$

When neighborhoods have the same mix of residents from the two groups, $Di_{mt} = 0$. Maximum neighborhood sorting occurs when all residents from one group are concentrated in the same neighborhoods and the remaining residents concentrated in the other neighborhoods, and in this case $Di_{mt} = 1$. Typically, a higher concentration of residents implies a lower within-neighborhood mix of residents from the two groups.

In constructing $Share^d_{mt}$ above, we used eight normalized national decile cutoffs. We can define poor and non-poor (or rich and non-rich) along each of the income cutoffs, and we construct dissimilarity indexes $DiShare^d_{mt}$ with respect to each of these income cutoffs. Similarly, for each inequality measure $Ratio^d_{mt}$, we construct a corresponding segregation measure $DiRatio^d_{mt}$.

In Figs. A4 and A5 in the Appendix, we plot across-municipality yearly means of $Share^d_{mt}$, $DiShare^d_{mt}$, $Ratio^d_{mt}$, and $DiRatio^d_{mt}$ for $d = 2, 8$ in terms of pre-tax income and disposable income, respectively. The figures show that along the bottom and top quintiles, inequality due to poverty and affluence have increased quite consistently. At the same time, corresponding segregation with respect to poverty and affluence developed similarly, reflecting growing neighborhood concentrations of low- and high-income residents in different neighborhoods. The trends we describe here are the clearest when it comes to disposable income. Table A3 in the Appendix provides summary statistics for our inequality and segregation measures along different deciles.

### 5.2. Distinguishing poverty and affluence effects on segregation

We now analyze the role of different parts of the municipal income distribution with regard to the relationship between inequality and segregation. Table 7 presents estimates from regressions (Eq. (3)) of changes in neighborhood dissimilarity indexes along normalized national decile cutoffs ($\Delta DiShare^d_{mt}$) on changes in shares of residents by the corresponding cutoffs ($\Delta Share^d_{mt}$).

Our point estimates for disposable income are mostly smaller than for pre-tax income. Once including the stayer control to rule out reverse causation and mechanical effects in columns (2) and (4), a clear pattern emerges with positive point estimates that are mostly statistically significant for decile cutoffs below the median ($d < 5$). This means that raising poverty rates increase neighborhood poverty dissimilarity.

In Fig. 5, we translate the estimates in columns (2) and (4) of Table 7 into estimates of how much inequality change can account for the growing segregation over time. We calculate (sample) mean five-year effects (with the help of Table A3 in the Appendix) of $Share^d_{mt}$ on $DiShare^d_{mt}$ and then divide this by mean $\Delta DiShare^d_{mt}$ to obtain the proportion of mean $\Delta DiShare^d_{mt}$ that the estimates can explain. We plot these translated point estimates with dots and 95% confidence intervals with bars (y-axis) for each decile cutoff (x-axis), and we censor the y-axis at the value of one.[33]

[32] Let $Income^d_t$ be income at the national decile $d$ in year $t$ and let $T$ denote the number of years. Then, $Proportion^d = [\sum_t (Income^d_t / Income^5_t)]/T$ for $d = 1, 2, 3, 4, 6, 7, 8, 9$ are the normalized national decile cutoffs. For municipality $m$ in year $t$ with median income $Income^5_{mt}$, $Share^d_{mt}$ is the share of the population with an income divided by $Income^5_{mt}$ that is less (more) than $Proportion^d$ where $d = 1, 2, 3, 4$ ($d = 6, 7, 8, 9$).

[33] The translated estimates can be high not only because the estimated inequality effect is large but also because the segregation change to be accounted for in the denominator is small. A translated estimate above a value of one means that segregation would have decreased in the counterfactual case without growing inequality.

**Table 7**
Effects of poverty and affluence rates on neighborhood dissimilarity.

| Dep. var. | Ind. var. | (1) Disposable income estimates | (2) | (3) Pre-tax income estimates | (4) |
|---|---|---|---|---|---|
| | | No stayer control | Stayer control | No stayer control | Stayer control |
| $\Delta DiShare^1$ | $\Delta Share^1$ | 0.206 | 1.008** | 0.765** | 1.130** |
| | | (0.285) | (0.293) | (0.119) | (0.321) |
| $\Delta DiShare^2$ | $\Delta Share^2$ | 0.356* | 0.882** | 0.491** | 0.783** |
| | | (0.147) | (0.163) | (0.0841) | (0.211) |
| $\Delta DiShare^3$ | $\Delta Share^3$ | 0.0805 | 0.418** | 0.479** | 0.736** |
| | | (0.123) | (0.128) | (0.0756) | (0.148) |
| $\Delta DiShare^4$ | $\Delta Share^4$ | −0.0423 | 0.136 | 0.616** | 0.915** |
| | | (0.106) | (0.115) | (0.0895) | (0.142) |
| $\Delta DiShare^6$ | $\Delta Share^6$ | −0.191* | −0.306* | 0.236** | 0.00308 |
| | | (0.0891) | (0.146) | (0.0640) | (0.0979) |
| $\Delta DiShare^7$ | $\Delta Share^7$ | −0.151* | −0.154 | 0.0226 | −0.0827 |
| | | (0.0683) | (0.151) | (0.0327) | (0.123) |
| $\Delta DiShare^8$ | $\Delta Share^8$ | −0.0743 | 0.0332 | −0.195** | −0.0820 |
| | | (0.0624) | (0.186) | (0.0517) | (0.176) |
| $\Delta DiShare^9$ | $\Delta Share^9$ | −0.250** | 0.193 | −0.471** | 0.107 |
| | | (0.0862) | (0.230) | (0.0981) | (0.257) |

Notes: There are 6670 observations of five-year changes (290 municipalities and 23 base years 1990–2012). All regressions include base-year dummies, the inequality complement ($\Delta\overline{Share}^{d}_{mt}$), and other basic covariates ($\boldsymbol{z}_{mt}$). See the notes of Table 3 for more details. We weight regressions by the working-age population in the base year, and we report standard errors clustered at the municipality level in parentheses.
* $p < 0.05$.
** $p < 0.01$.

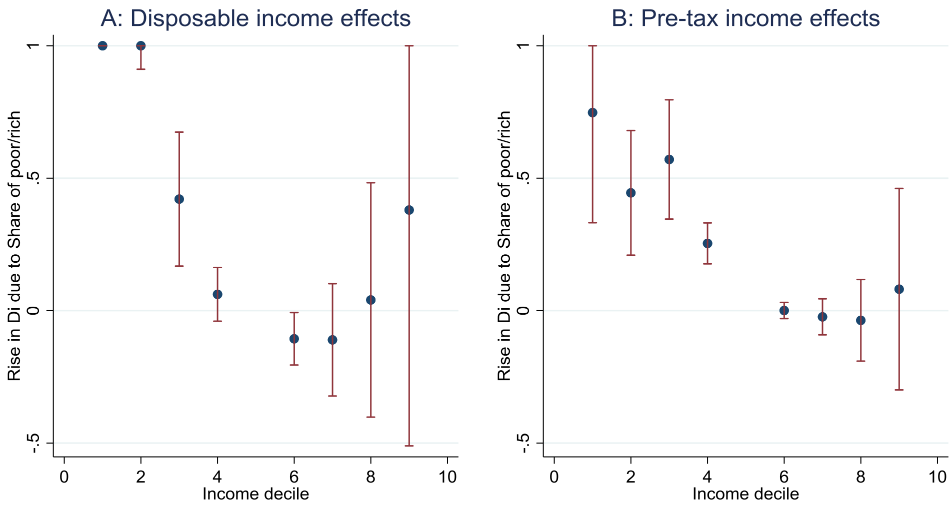


**Fig. 5.** Segregation changes accounted for by poverty and affluence rate changes, Notes: We calculate the proportion of dissimilarity index change over time that can be accounted for using point estimates from regressions of $\Delta DiShare^{d}_{mt}$ on $\Delta Share^{d}_{mt}$ (from columns 2 and 4 in Table 7). The point estimates are separately multiplied by mean $\Delta Share^{d}_{mt}$ and divided by mean $\Delta DiShare^{d}_{mt}$ (from Table A3 in the Appendix) for each decile $d = 1, 2, 3, 4, 6, 7, 8, 9$. Similarly, we construct confidence intervals from the standard error estimates in Table 7. Y-values have been censored at the value of one.

Fig. 5 shows that our estimated impacts of poverty rates can account for a large part, if not all, of the rise in poverty dissimilarity between neighborhoods, especially when using the first to third decile cutoffs. To prevent neighborhood concentration of low-income residents, policymakers could decrease pre-tax income poverty by raising the skill levels of residents with low pre-tax incomes.

Having investigated the importance of inequality due to tail thickness for segregation, we now move on to the importance of tail length. Table 8 presents estimates from regressions (Eq. (3)) of changes in neighborhood dissimilarity indexes

**Table 8**
Effects of relative incomes on neighborhood dissimilarity.

| Dep. var. | Ind. var. | (1) Disposable income estimates | (2) | (3) Pre-tax income estimates | (4) |
|---|---|---|---|---|---|
| | | No stayer control | Stayer control | No stayer control | Stayer control |
| $\Delta DiRatio^1$ | $\Delta Ratio^1$ | −0.135* | −0.355** | 0.917** | 2.217** |
| | | (0.0645) | (0.0931) | (0.229) | (0.411) |
| $\Delta DiRatio^2$ | $\Delta Ratio^2$ | −0.0234 | −0.582** | −0.112** | −0.241** |
| | | (0.163) | (0.113) | (0.0200) | (0.0598) |
| $\Delta DiRatio^3$ | $\Delta Ratio^3$ | −0.0549 | −0.230* | −0.182** | −0.248** |
| | | (0.139) | (0.0893) | (0.0232) | (0.0333) |
| $\Delta DiRatio^4$ | $\Delta Ratio^4$ | 0.141 | 0.0901 | −0.259** | −0.340** |
| | | (0.201) | (0.168) | (0.0308) | (0.0545) |
| $\Delta DiRatio^6$ | $\Delta Ratio^6$ | −0.0383 | −0.0518 | 0.0634* | −0.00834 |
| | | (0.101) | (0.148) | (0.0295) | (0.0807) |
| $\Delta DiRatio^7$ | $\Delta Ratio^7$ | 0.00323 | 0.0800 | 0.0165 | 0.0215 |
| | | (0.0564) | (0.114) | (0.0118) | (0.0688) |
| $\Delta DiRatio^8$ | $\Delta Ratio^8$ | 0.0949** | 0.166 | −0.00620 | 0.0529 |
| | | (0.0269) | (0.0879) | (0.0122) | (0.0611) |
| $\Delta DiRatio^9$ | $\Delta Ratio^9$ | 0.0199 | 0.0609 | 0.00284 | 0.0644 |
| | | (0.0171) | (0.0561) | (0.00955) | (0.0442) |

Notes: There are 6670 observations of five-year changes (290 municipalities and 23 base years 1990–2012). All regressions include base-year dummies, the inequality complement ($\Delta\overline{Ratio}^d_{mt}$), and other basic covariates ($\boldsymbol{z}_{mt}$). See the notes of Table 3 for more details. We weight regressions by the working-age population in the base year, and we report standard errors clustered at the municipality level in parentheses.
* $p < 0.05$,.
** $p < 0.01$.

along municipal income decile cutoffs ($\Delta DiRatio^d_{mt}$) on changes in municipal ratios of decile incomes to the median income ($\Delta Ratio^d_{mt}$). In Fig. 6, we translate the estimates in columns (2) and (4) of Table 8 into estimates of how much inequality change can account for the growing segregation over time like in Fig. 5.

When including the stayer control in columns (2) and (4) in Table 8, we mostly find negative point estimates that are statistically significant for decile cutoffs below the median. This means that raising relative incomes of low-income residents decreases the poverty dissimilarity between neighborhoods. Fig. 6 shows that the estimated effects are sizeable in terms of implications for neighborhood poverty dissimilarity. Thus, Fig. 6 largely confirms what we observed in Fig. 5, namely that lower-tail inequality is important for poverty segregation.

## 6. Concluding discussion

Previous research documented correlations between changes in income inequality and residential segregation by income across neighborhoods. However, few policy conclusions could be drawn regarding whether and which types of public policies could prevent segregation due to residential sorting. Using richer full-population data for Sweden 1990–2017, we analyzed how changing policy-relevant determinants of income inequality affects residential sorting and segregation in Swedish municipalities. We took advantage of how in-moving residents change the municipal income distribution and inequality to rule out reverse causation and mechanical effects. Moreover, we relied on changes in the tax and transfer system to estimate the effects of public redistribution.

Our main result is that reducing disposable income inequality has limited residential sorting effects on segregation. We also found that increasing pre-tax income inequality can account for the entire dramatic surge in segregation since the 1990s, mainly because growing shares of low-income residents can explain the rising concentration of such residents in certain neighborhoods. Moreover, our results show that the education composition is the main driver of the influence of pre-tax income inequality on segregation due to residential sorting.

In terms of policy recommendations, our results indicate that taxes and transfers affecting disposable incomes, e.g., progressive labor income taxes, capital income taxes, and housing and child allowances, cannot prevent residential segregation in Sweden. Regarding generalizability, we believe that this result is relevant for relatively developed and egalitarian countries with extensive public redistribution and good welfare services. Fine-tuning the tax and transfer system additionally in such contexts does not matter much for residential segregation. In less developed or more unequal countries, pocketbook concerns likely put stronger restrictions on residential neighborhood choices, and public redistribution may be a more promising tool for affecting those choices and thereby segregation. However, our results might indicate that residents treat transfers as temporary income that only marginally enter their long-run housing decisions. If one believes in that interpretation, then the prospects for preventing segregation with redistribution are grim in a wider variety of contexts.

Our findings strongly suggest that policymakers who want to fight segregation by reducing inequality should focus on equalizing pre-tax incomes by combatting poverty due to low skill and education levels. However, raising skill and educa-

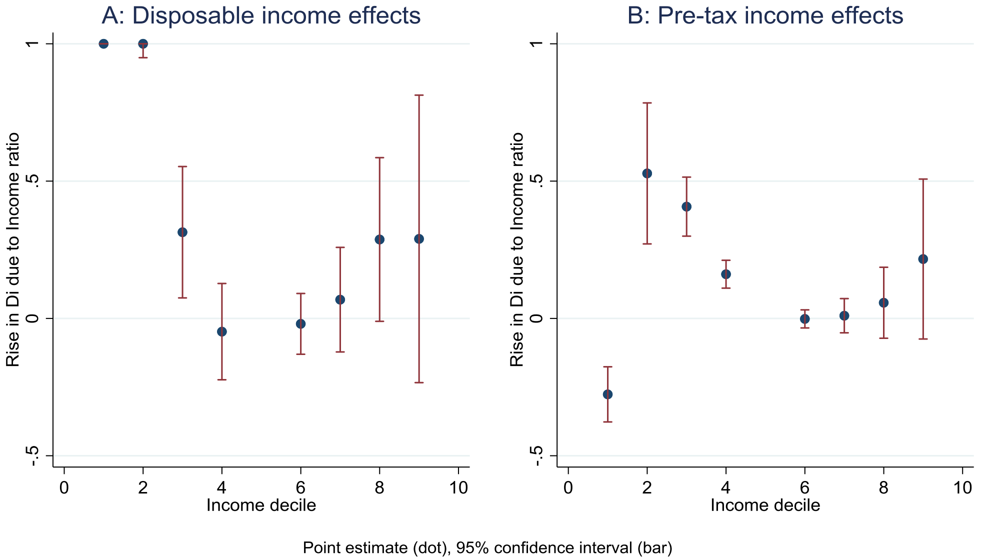


**Fig. 6.** Segregation changes accounted for by relative income changes, Notes: We calculate the proportion of dissimilarity index change over time that can be accounted for using point estimates from regressions of $\Delta DiRatio^{d}_{mt}$ on $\Delta Ratio^{d}_{mt}$ (from columns 2 and 4 in Table 8). The point estimates are separately multiplied by mean $\Delta Ratio^{d}_{mt}$ and divided by mean $\Delta DiRatio^{d}_{mt}$ (from Table A3 in the Appendix) for each decile $d = 1, 2, 3, 4, 6, 7, 8, 9$. Similarly, we construct confidence intervals from the standard error estimates in Table 8. Y-values have been censored at the value of one.

tion levels is challenging and takes time. In the Swedish context, labor market programs targeting working-age individuals with weak ties to the labor market are potentially effective measures. In the long run, we believe that top priority should go to interventions that improve school attainments and cognitive abilities of the children exhibiting the weakest results, especially those at risk of not completing high school. Policies targeting low-income neighborhoods could be particularly effective. Residential segregation by skill and education levels may reflect deeper universal preferences for similar neighbors. If so, our results provide broader lessons. While schools and universities are free of charge and in principle available to everyone in Sweden, barriers to entry are higher in many other countries. In these countries, policymakers could focus on lowering those barriers.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

# Appendix

**Table A1**
Summary statistics.

| | (1) Base-year | (2) | (3) Five-year change | (4) |
|---|---|---|---|---|
| | Mean | Std. dev. | Mean | Std. dev. |
| *Sd* disposable income | 1.703 | 0.478 | 0.144 | 0.203 |
| *Sd* pre-tax income | 4.095 | 0.426 | 0.114 | 0.268 |
| *Nsi* disposable income | 0.125 | 0.057 | 0.007 | 0.028 |
| *Nsi* pre-tax income | 0.191 | 0.085 | 0.011 | 0.036 |
| Education: no high-school degree | 0.232 | 0.078 | −0.037 | 0.029 |
| Education: high-school degree | 0.488 | 0.074 | −0.007 | 0.058 |
| Education: university degree | 0.280 | 0.116 | 0.044 | 0.072 |
| Born: Sweden | 0.878 | 0.064 | −0.015 | 0.011 |
| Born: Europe but outside Sweden | 0.070 | 0.033 | 0.002 | 0.005 |
| Born: outside Europe | 0.052 | 0.039 | 0.013 | 0.011 |
| Age $<$ 21 | 0.252 | 0.025 | −0.004 | 0.007 |
| Age $>$ 65 | 0.165 | 0.033 | 0.005 | 0.012 |
| Age: 21–25 | 0.064 | 0.016 | 0.000 | 0.007 |
| Age: 26–30 | 0.067 | 0.018 | −0.001 | 0.007 |
| Age: 31–35 | 0.068 | 0.012 | −0.001 | 0.006 |
| Age: 36–40 | 0.069 | 0.007 | −0.001 | 0.006 |
| Age: 41–45 | 0.069 | 0.006 | −0.002 | 0.006 |
| Age: 46–50 | 0.068 | 0.007 | −0.001 | 0.006 |
| Age: 51–55 | 0.064 | 0.008 | 0.002 | 0.009 |
| Age: 56–60 | 0.059 | 0.010 | 0.002 | 0.009 |
| Age: 61–65 | 0.054 | 0.011 | 0.002 | 0.009 |
| Population (change divided by base level) | 149,717 | 223,753 | 0.030 | 0.041 |
| Housing space ($m^2$ per person) | 43.544 | 3.594 | 0.152 | 1.856 |

Note: We use working-age population weights.

**Table A2**
The influence of inequality on segregation treating each family as an income unit.

| Dependent variable: $\Delta Nsi$ | (1) | (2) | (3) |
|---|---|---|---|
| Independent variable: $\Delta Sd$ | A: Disposable income estimates | | |
| No stayer control | 0.0835** | 0.0795** | 0.0679** |
| | (0.0136) | (0.0146) | (0.0138) |
| With stayer control ($\Delta Sd^{stay}$) | 0.0460* | 0.0338 | 0.0190 |
| | (0.0186) | (0.0232) | (0.0365) |
| | B: Pre-tax income estimates | | |
| No stayer control | 0.0899** | 0.0943** | 0.102** |
| | (0.00825) | (0.0111) | (0.00898) |
| With stayer control ($\Delta Sd^{stay}$) | 0.0759** | 0.0800** | 0.113** |
| | (0.0118) | (0.0138) | (0.0128) |
| Base-year dummies | Yes | Yes | Yes |
| Inequality complement ($\Delta\overline{Sd}$) | No | Yes | Yes |
| Other covariates ($\boldsymbol{z}$) | No | No | Yes |

Notes: There are 6670 observations of five-year changes (290 municipalities and 23 base years 1990–2012). In constructing the *Sd* and *Nsi* variables, we treat each family as an income unit and use the mean income among the working-age family members. See the notes of Table 3 for more details on the covariates. We weight regressions by the working-age population in the base year, and we report standard errors clustered at the municipality level in parentheses.

* $p < 0.05$.

** $p < 0.01$.

**Table A3**
Summary statistics: inequality and segregation variables along different deciles.

| | (1) Disposable income | (2) | (3) | (4) Pre-tax income | (5) | (6) |
|---|---|---|---|---|---|---|
| Variable | Base-year | Change | $\Delta In^{stay}$ | Base-year | Change | $\Delta In^{stay}$ |
| | A: Shares and income ratios of poor and rich | | | | | |
| $Share^1$ | 0.095 | 0.013 | 0.012 | 0.126 | 0.006 | 0.009 |
| $Share^2$ | 0.187 | 0.020 | 0.012 | 0.202 | 0.005 | 0.003 |
| $Share^3$ | 0.288 | 0.015 | 0.003 | 0.297 | 0.006 | −0.004 |
| $Share^4$ | 0.395 | 0.007 | −0.006 | 0.398 | 0.003 | −0.009 |
| $Share^6$ | 0.396 | 0.004 | 0.015 | 0.401 | 0.002 | 0.012 |
| $Share^7$ | 0.292 | 0.007 | 0.016 | 0.303 | 0.003 | 0.011 |
| $Share^8$ | 0.189 | 0.010 | 0.015 | 0.202 | 0.005 | 0.010 |
| $Share^9$ | 0.091 | 0.008 | 0.010 | 0.099 | 0.005 | 0.008 |
| $Ratio^1$ | 0.460 | −0.037 | −0.037 | 0.004 | −0.003 | −0.003 |
| $Ratio^2$ | 0.659 | −0.031 | −0.021 | 0.161 | −0.020 | −0.012 |
| $Ratio^3$ | 0.788 | −0.019 | −0.004 | 0.484 | −0.015 | 0.017 |
| $Ratio^4$ | 0.899 | −0.008 | 0.007 | 0.780 | −0.005 | 0.025 |
| $Ratio^6$ | 1.102 | 0.005 | 0.017 | 1.167 | 0.003 | 0.017 |
| $Ratio^7$ | 1.218 | 0.010 | 0.022 | 1.327 | 0.006 | 0.020 |
| $Ratio^8$ | 1.367 | 0.018 | 0.029 | 1.530 | 0.013 | 0.028 |
| $Ratio^9$ | 1.623 | 0.033 | 0.045 | 1.895 | 0.032 | 0.053 |
| | B: Dissimilarity indexes | | | | | |
| $DiShare^1$ | 0.154 | 0.003 | | 0.187 | 0.009 | |
| $DiShare^2$ | 0.149 | 0.012 | | 0.162 | 0.008 | |
| $DiShare^3$ | 0.148 | 0.014 | | 0.151 | 0.008 | |
| $DiShare^4$ | 0.149 | 0.015 | | 0.138 | 0.011 | |
| $DiShare^6$ | 0.160 | 0.012 | | 0.137 | 0.012 | |
| $DiShare^7$ | 0.173 | 0.010 | | 0.147 | 0.012 | |
| $DiShare^8$ | 0.192 | 0.008 | | 0.167 | 0.010 | |
| $DiShare^9$ | 0.228 | 0.004 | | 0.207 | 0.007 | |
| $DiRatio^1$ | 0.154 | 0.003 | | 0.187 | 0.009 | |
| $DiRatio^2$ | 0.149 | 0.012 | | 0.162 | 0.008 | |
| $DiRatio^3$ | 0.148 | 0.014 | | 0.151 | 0.008 | |
| $DiRatio^4$ | 0.149 | 0.015 | | 0.138 | 0.011 | |
| $DiRatio^6$ | 0.160 | 0.012 | | 0.137 | 0.012 | |
| $DiRatio^7$ | 0.173 | 0.010 | | 0.147 | 0.012 | |
| $DiRatio^8$ | 0.192 | 0.008 | | 0.167 | 0.010 | |
| $DiRatio^9$ | 0.228 | 0.004 | | 0.207 | 0.007 | |

Notes: We report means (working-age population weights) for base-year level variables in columns (1) and (4), for five-year changes in columns (2) and (5), and for the stayer covariate version of the variables when applicable in columns (3) and (6).

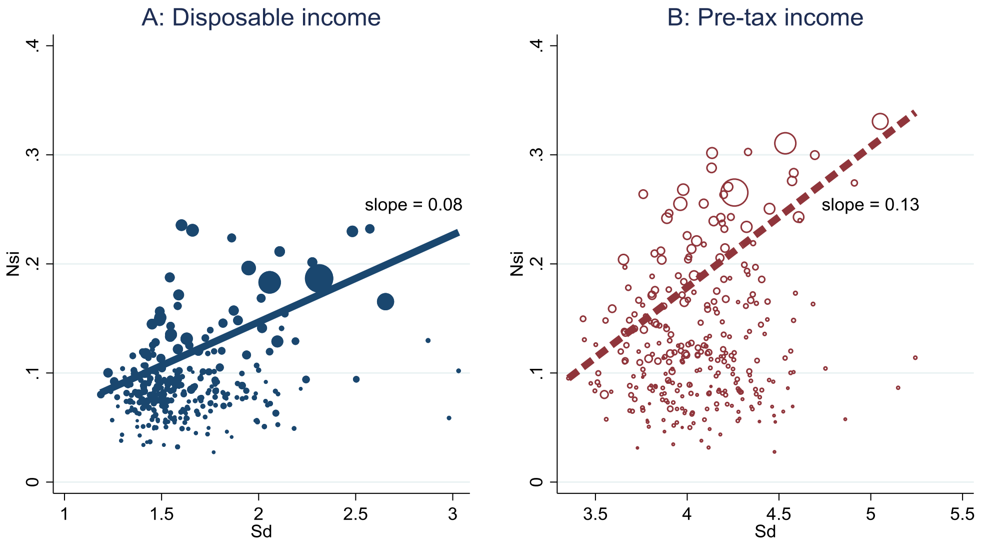


**Fig. A1.** Municipal correlations between inequality and segregation, Notes: Each dot represents one municipality and the dots are weighted by the working-age population. We report estimated slope coefficients from (weighted) regressions of across-year municipal mean $Nsi_{mt}$ on $Sd_{mt}$.

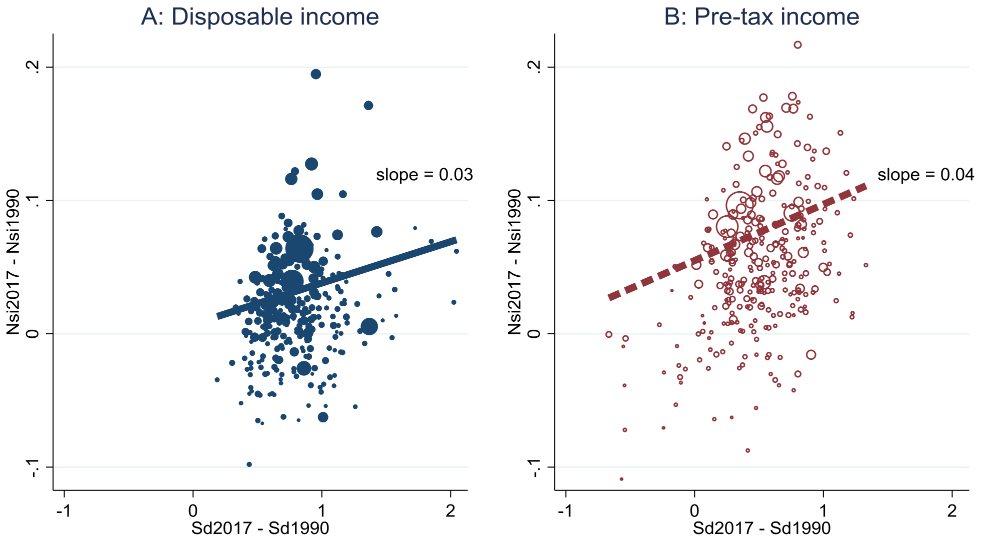


**Fig. A2.** Municipal correlations between changes in inequality and segregation, Notes: Each dot represents one municipality and the dots are weighted by the working-age population. We report estimated slope coefficients from (weighted) regressions of $Nsi_{m,2017} - Nsi_{m,1990}$ on $Sd_{m,2017} - Sd_{m,1990}$.

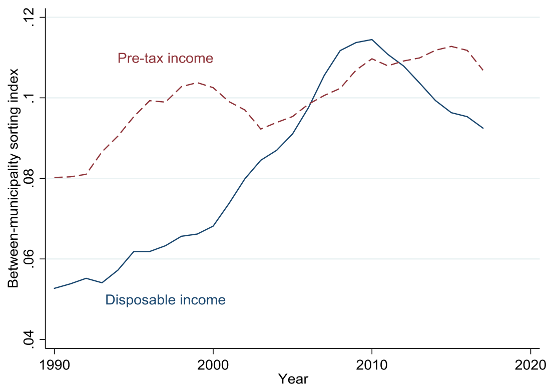


**Fig. A3.** Between-municipality inequality over time, Note: We report the Nsi measure treating municipalities (instead of neighborhoods) as subunits.

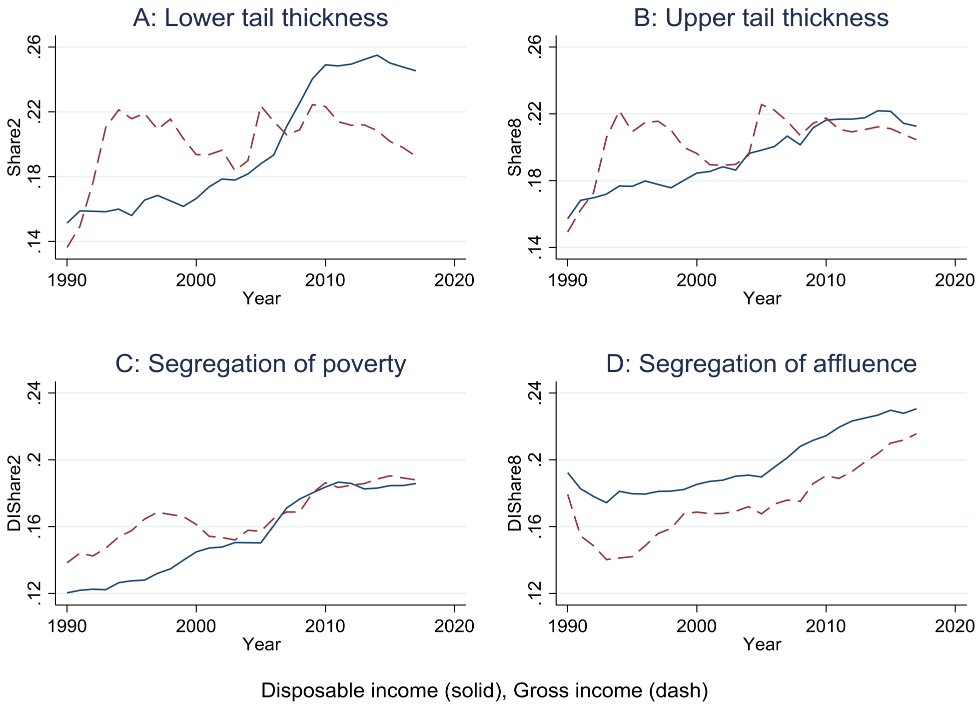


**Fig. A4.** Inequality and segregation over time: Poverty/affluence rates/dissimilarity indexes, Notes: The municipal poverty (affluence) rate is the municipal share of residents with less (more) income than the 2nd (8th) normalized national decile cutoff. Dissimilarity indexes are defined with respect to the corresponding cutoffs. We report across-municipality yearly means (working-age population weights).

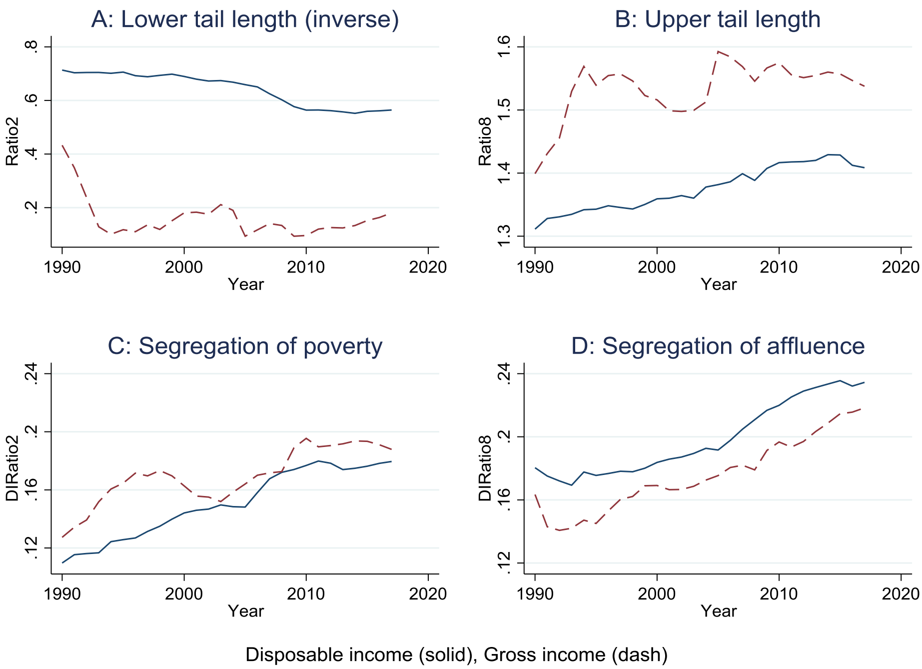


**Fig. A5.** Inequality and segregation over time: Relative income and dissimilarity indexes, Notes: The municipal relative income of poor (rich) residents is the municipal 2nd (8th) decile cutoff divided by the municipal median income. Dissimilarity indexes are defined with respect to the corresponding cutoffs. We report across-municipality yearly means (working-age population weights).

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