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Research paper

The influence of global and domestic uncertainty on electricity supply: A study of Swedish power sources

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ABSTRACT

Developing sustainable energy systems through system integration and sector coupling may involve permeating previous isolated and idiosyncratic reactions through the whole system. This study examines supply side dynamics of how uncertainty and spot prices influence electric power supply in an internationally connected electricity system. By applying quantile methods, the study reveals highly nonlinear and asymmetric responses in supplied electricity given a change in uncertainty or system spot prices. The findings show that while the total supply of electricity is largely unaffected by uncertainty and spot price, both supply level and changes in power supply for specific dispatchable power sources are influenced differently depending on the type of uncertainty (domestic or global). The findings also show that the response structure induced by uncertainty and spot price seems to be largely uniform and power source specific. This has implications for creating, amongst other things, integrated systems, and sector coupling, where there is a need for inexpensive excess power supply.
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1. Introduction

Energy has been an essential component for human society, especially since the beginning of the industrial revolution (Chu and Majumdar, 2012) Access to affordable and clean energy is a fundamental objective in achieving sustainable development, as outlined in the sustainable development goal 7 (SDG7). The urgency of global challenges, such as accelerating climate change and resource depletion, push for transformative policies and systemic change to global energy supply systems. The challenges are compounded by the fact that energy demand continues to increase (IEA, 2021b). The need for clean energy is urgent, as highlighted in sustainable development goal number 7, and strongly related to sustainable development goals 8 and 9 (UN General Assembly, 2015). Renewable electricity is especially important, and worldwide electricity demand is expected to double in the next 30 years, as electric power is considered the key energy carrier in a sustainable energy system (Bogdanov et al., 2019, 2021). It is also estimated that up to the year 2050, three-quarters of emission reductions will take place in the power sector in order to meet climate goals (IEA, 2021a, 2022a).

Moreover, energy efficiency and widespread electrification are considered essential factors to achieve a deep decarbonisation of a modern and industrialised society (Bogdanov et al., 2019; IEA, 2021a). Even though renewable power generation is available in many counties, it will nonetheless be difficult to meet increasing global demand for electric power solely with new renewable power capacity (IPCC, 2022). Therefore, besides various forms of energy storage, smart grids and demand-side management (IPCC, 2022; Luc Van Nuffel et al., 2018), a sustainable energy system will likely have to involve concepts such as system integration (O'Malley Mark et al., 2016) and sector coupling (Luc Van Nuffel et al., 2018). On the supply side, sector integration and sector coupling involve, amongst other things, power-to-X technologies. Power to-X means that in times of excess (inexpensive) power supply, electric power is converted to other types of energy carriers, e.g., gas and fuels, in order to be reconverted in times of electric power shortages (Rego de Vasconcelos and Lavoie, 2019). However, the process needs to have at least some form of cost efficiency as energy losses are quite high (Escamilla et al., 2022). Despite energy losses and cost challenges, sector coupling and sector integration concepts are seen as promising pathways towards relatively affordable, efficient, reliable and sustainable energy (EU, 2020; Paiho et al., 2021). Additionally, in industrial sectors, excess heat is another important source of energy, where the heat is either converted to electric power or recovered in other ways (Champier, 2017; Svensson et al., 2019). When taken as a whole, the development of sustainable energy systems will likely lead to a diverse, highly interconnected network of energy systems (Lund et al., 2017; Rinaldi et al., 2001). The level of

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interdependency will increase not only between different components of the energy systems, but also across various sectors of the economy (Amin and Wollenberg, 2005; Ilo and Schultis, 2022).

Recent global events, particularly Russia's invasion of Ukraine, have heightened concerns about the resilience and reliability of the electric power supply, as well as the uncertainty influencing the energy system (Karkowska and Urjasz, 2023). The Russian invasion triggered a global energy crisis (Astrov et al., 2022; Kalogiannidis et al., 2022), exposing vulnerabilities in the European energy supply and leading to skyrocketing electricity prices in Scandinavian countries (Jääskeläinen et al., 2022).

From the perspective of the impacts of uncertainty, recent events have starkly revealed a profound lack of understanding regarding how global uncertainties influence energy systems, particularly electricity system. Until recently, uncertainty chocks and energy is a largely unexplored area. Even today, research remains sparse, despite some recent attempts to explore, for instance, the relation between economic policy uncertainty and energy generation in China (Wei et al., 2021) or the influence of economic policy uncertainty on renewable energy utilisation (Li et al., 2023). There is also some very recent research aimed at developing an energy-related uncertainty index (EUI), which analyses shocks to energy related markets in 28 countries (Dang et al., 2023).

Other literature studying uncertainty in relation to the supply side variations in electricity generation mostly concerns technical uncertainties (Allwyn et al., 2023; Blanco et al., 2018; Islam and Roy, 2023; Zare Oskouei et al., 2021). Another area of uncertainty studies covers difficulties in grid management such as forecasting renewable power generation such as photovoltaic (Antonanzas et al., 2016; Sobri et al., 2018) and wind power generation (Foley et al., 2012; Zhang et al., 2014). Besides the technical uncertainty aspects for non-dispatchable power generation (solar and wind power), uncertainties are mostly discussed from either individual power sources or as a modelling perspective comparing different techniques (Ehsan and Yang, 2019). The uncertainty components mostly consist of varying price levels (Nowotarski and Weron, 2018), economic growth, inflation rates, various costs (Hirth et al., 2015) and taxes (Ehsan and Yang, 2019; Möst and Keles, 2010). Thus, uncertainties mainly depart from the intermittent generating capacity of renewables and prediction errors from random variations in data, models and network errors (Singh et al., 2022).

When it comes to understanding differences between uncertainties, e.g., global vs domestic, market vs economic policy etc, there is almost no applications on existing systems. Thus there is a substantial knowledge gap in understanding specific uncertainties and how these influence electric power supply.

Previous research on sector coupling and sector integration, mainly explores various power-to-gas or power-to-liquid solutions, including hydrogen (Buttler and Spliethoff, 2018; Dodds et al., 2015; Gahleitner, 2013) and how to integrate and manage a high share of renewables in an integrated energy system (Onen et al., 2022). Other studied areas are synergies in energy system and electricity storage (Brown et al., 2018) and economics of storage solutions (Gautam et al., 2022; Haas et al., 2022).

It should also be noted that, although the pursuit of sustainable energy systems is a global endeavour, the actual implementation of these systems will be carried out on a local or, at most, a regional level (Korhonen et al., 2018). Thus, extensive sector coupling and integrated systems means that traditionally separate sectors and actors will eventually be highly connected through the energy (electric power) system. This situation creates new challenges for individual actors as well as for policy makers (Creutzig et al., 2017). Highly connected systems can potentially change the dynamics for specific sectors and subsystems as well as for the system viewed from a wider perspective (Brinkerink et al., 2019). For example, previously isolated events can, in a connected system, lead to system wide implications (Wu et al., 2020). Vice versa, global, or regional incidents can spread to local systems more easily. Integrating (or coupling) sectors means adding another layer of complexity to an already complex system. Thus, there is reason to suspect that highly integrated systems and sectors likely also entail sharing elements of risk and uncertainty, which exposes the whole system to hazardous events with potentially systemwide effects (Ravadanegh et al., 2022). In this way, sector integration (sector coupling) means that the system must be viewed as a whole, where the system is managed across different sectors and subsystems, including multiple energy carriers and consumption areas (EU, 2020; Luc Van Nuffel et al., 2018).

As mentioned before, little attention has been paid to empirically examining how global and domestic uncertainties impact physically supplied electric power on regional or power source level. The aim of this study is therefore to thoroughly explore the supply side dynamics of Swedish electric power sources. Accordingly, this paper investigates how global and domestic uncertainty, as well as system spot prices, influence power output from the main dispatchable power sources in Sweden. Although a small country, Sweden is still one of the top per-capita users of electricity globally. For example, in 2020, electricity constituted around 32% of Swedish total energy supply[1] (Swedish Energy Agency, 2022) while electricity use in 2020 was 12.3 MWh/per capita (IEA, 2022b) (See Fig. 1 for Swedish electric power supply and demand in 2020). Digitalisation, electrification and rapid technological development, including a new green industrialisation of the northern parts of Sweden, means that total electricity supply in Sweden will increase to over 300 TWh by 2045 (Jenny Gode et al., 2021). This means almost doubling the current levels of electricity utilisation. Additionally, in the first half of 2022, Sweden became Europe's largest net electric power exporter, supplying 18.9 TWh[2] to the Scandinavian and European market. Being part of a more integrated European electricity system, Swedish power supply is exposed not only to seasonal demand variations and variations in industrial activity influenced by exports and global trade, but also market dynamics influenced by the structure of the European energy system. This means potentially large and irregular variations in electric power supply, with increasing challenges to a stable electricity system (kraftnät, 2019).

In order to understand the prospect for developing a sustainable and resilient energy system involving sector coupling and integrated systems, detailed investigations of the Swedish electricity system are needed. Therefore, this paper examines the predictive power of uncertainty shocks (information gained) when studying Swedish electricity supply. By applying quantile methods, nonlinear behaviour can effectively be analysed and described. Additionally, by controlling for factors that can influence power supply, this study provides a robust and comprehensive understanding of information-feedback signals in dispatchable power supply. The study further differs from previous research by also examining asymmetric relationships, with and without seasonality in data.

As will be shown in this paper, studying total supply of electricity does not reveal important behavioural responses induced by uncertainty. This implies that information-feedback responses occur in subsystems and/or in system components but not on an aggregated system level. Also, Swedish power supply seems to be more sensitive to global uncertainty compared to domestic uncertainty. This means that in order to create resource efficient

[1] Total energy supplied in Sweden 2020 was 508 TWh, electricity 161 TWh.

[2] https://www.scb.se/en0108-en

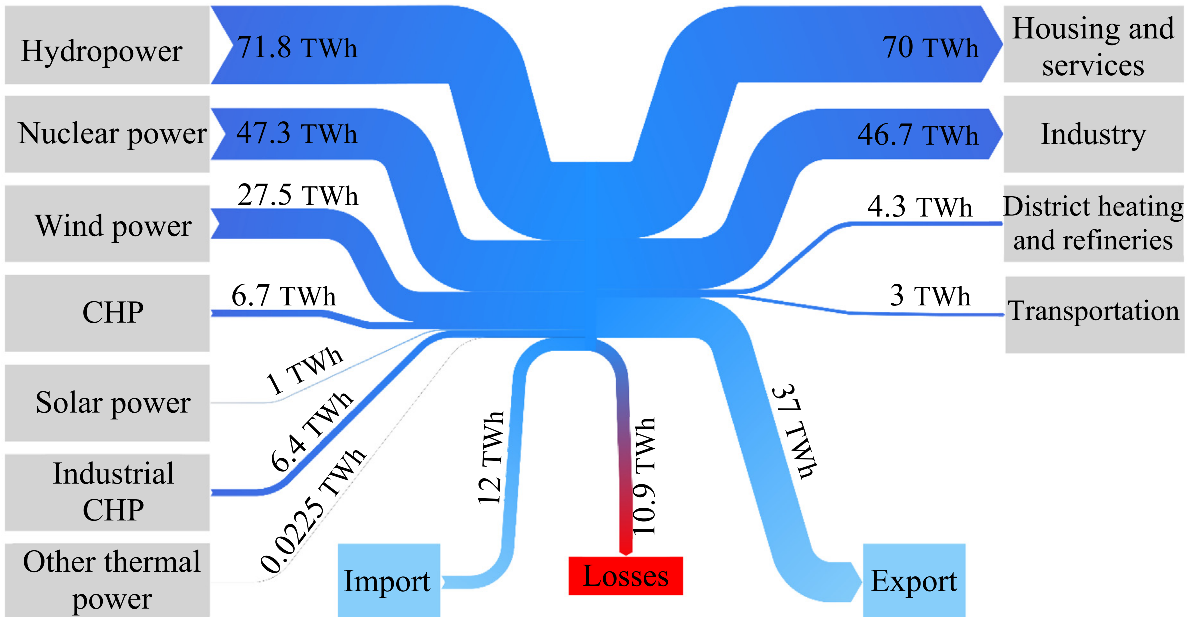

Fig. 1. Swedish electric power balance year 2020.

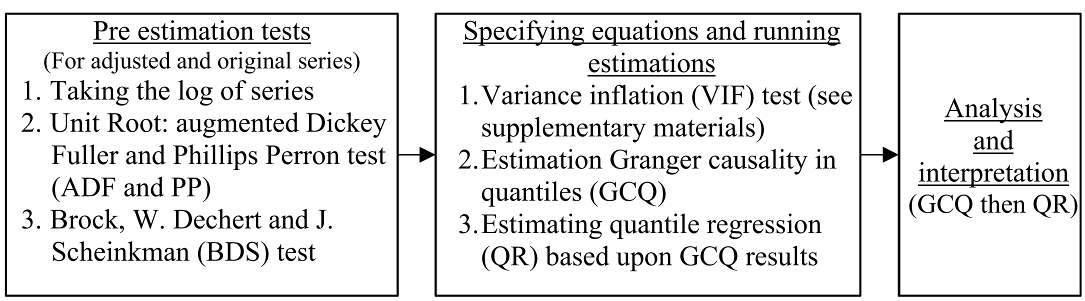

Fig. 2. Illustration of methodological steps and procedures.

systems, decision makers will have to tailor policies for specific types of system dynamics (e.g., reactions to different types of uncertainty, etc.) based on idiosyncratic circumstances. For example, this can be helpful when aggregating, coordinating, and operating diverse power sources (Chen et al., 2023), and for frequency stability in the Nordic system (Weihs et al., 2020).

2. Methodology and materials

The analysis in this paper, presented in Fig. 2, consists of two methodological approaches, where the first method is the Granger Causality in Quantiles (GCQ) test developed by Troster (2018). The second method applied is Quantile Regression (QR) developed by Koenker and Bassett (1978) and Koenker and d'Orey (1994).

The QR approach provides greater details than a conditional mean regression analysis, when the analysed data are characterised by nonlinearity and non-normality (Koenker and Bassett, 1978). Also, directional and causal relations in quantiles may differ markedly compared to linear models, as the quantile based approach captures dynamic, nonlinear and asymmetrical relationships considering the whole distribution (Khan et al., 2020; Koenker and Bassett, 1978; Troster, 2018). The GCQ method tests the predictive power of an explanatory variable against the dependent variable (in this case power supply) while controlling for situations where values of the dependent variable in one period depends on its own previous values (time varying auto regressive models). The GCQ is a well-established method for investigating nonlinear causal relations (Troster et al., 2018; Wadström et al., 2019). It has also been proven to be sensitive and robust in terms of the predictive power, even for small samples (Troster, 2018).

The GCQ method presents a trade-off between computational efficiency and model precision. Higher-resolution analyses give better causality detail but require more data. In our study, we tested ten quantiles with three lags, adjusting the subsample size to assess the GCQ models robustness. The results revealed minor differences between these models, even with reduced subsampling. Choice of methods and model specification in this study is comparable to other studies, for example (Mohammed and Mellit, 2023; Raggad, 2023)

Table 1
Descriptive statistics.

Variable name	Mean	Median	Max	Min	Std. Dev.	Skew	Kurt	J–B
Total power supply (Total)	9.513	9.520	9.805	9.177	0.150	−0.135	1.992	13.798***
Nuclear power supply (Nuclear)	8.526	8.552	8.906	7.601	0.237	−0.808	3.413	35.238***
Hydro power supply (Hydro)	8.614	8.644	8.973	7.880	0.193	−0.727	3.293	27.835***
Back pressure power supply (BPP)	6.015	6.371	7.456	2.079	1.033	−1.115	3.988	75.324***
Industrial back pressure power (Ind BPP)	6.136	6.161	6.495	5.642	0.175	−0.619	3.027	19.393***
Conventional power supply (Conv)	3.910	3.998	6.033	0.000	0.754	−0.965	6.544	206.254***
Power imports (Imp)	6.862	6.964	7.959	4.860	0.554	−0.829	3.599	39.353***
Swedish EPU (SWEEPU)	4.526	4.540	5.210	3.984	0.210	−0.068	2.917	0.320
Global EPU (GEPU)	4.767	4.715	6.080	3.947	0.485	0.456	2.425	14.728***
Equity market volatility (EMV)	3.010	2.970	4.246	2.259	0.330	0.809	3.906	43.532***
Economic tendency indicator (ETI)	4.602	4.621	4.792	4.099	0.107	−1.370	6.166	221.986***
Nord Pool system spot price (P)	5.576	5.633	7.325	3.189	0.592	−0.464	4.154	27.771***
Seasonally adjusted								
Total power supply (Total)	9.521	9.520	9.683	9.358	0.054	−0.195	3.111	2.079
Nuclear power supply (Nuclear)	8.538	8.583	8.895	8.007	0.162	−0.810	3.316	34.538***
Hydro power supply (Hydro)	8.620	8.640	9.028	8.056	0.150	−0.378	3.414	9.428***
Back pressure power supply (BPP)	6.332	6.367	7.009	5.044	0.313	−0.782	4.506	59.748***
Industrial back pressure power (Ind BPP)	6.139	6.178	6.371	5.673	0.148	−0.742	2.587	30.051***
Conventional power supply (Conv)	3.950	3.982	6.094	0.162	0.680	−0.949	7.348	285.128***
Power imports (Imp)	6.885	6.974	8.103	5.254	0.513	−0.773	3.680	36.117***

Note: Series are in log level, observations $n = 304$, from January 1997 to April 2022. J–B indicate the Jarque and Berea test for normality where *, **, *** represents the 10%, 5% and 1% significance level. Electricity data collected from Statistics Sweden, Swedish economic tendency indicator collected from National institute of economic research and uncertainty trackers indices collected from economic policy uncertainty.

Although the GCQ provides information about the causal directionality, it says nothing about the magnitude of the impact or co-movement of the studied variables. The opposite can be said about QR as the method provides estimates of the co-movements, but not about directionality or causal relations. Results from the two methods will therefore be combined, and in this study, Granger causality is an essential factor when analysing regression results. Hence, the GCQ test is given precedence over the QR with regards to the causal relations and the directionality. Dependent and independent variables are log-transformed as the logarithmic transformation of variables dampens exponential growth patterns and reduces heteroscedasticity (i.e., stabilises variance). The analysis is performed on both log-transformed variables $\ln Y_\tau^{PS}$ and on logarithmic differences $\ln\left(Y_t^{PS}\right) - \ln\left(Y_{t-1}^{PS}\right), \ln\left(X_{i,t}\right) - \ln(X_{i,t-1})$. This in order to capture both effects in level and effects in changes.

2.1. Materials

The analysis includes (see Table 1) seven dependent variables (Y_t^{PS}), three control variables and three explanatory variables (for a full description of data, see supplementary material). The dependant variables are total power supply, nuclear power supply (condensation), hydro power supply (including pumped storage power net), turbine back pressure power supply (including cogenerating thermal plants), industrial turbine back pressure power supply, conventional power supply (thermal condensation) and power imports. The data consist of monthly observations of electric power supply during the period January 1997 to April 2022 (see Appendices A and B for graphical presentations of power supply series). The flow of electricity (energy) is measured in GWh, except for power imports, which is measured in MWh/h (MW). The period has been selected with regards to the deregulation of the Swedish electricity market in 1996. Trades on the Swedish electricity market (Nordpool) are settled on either the day-ahead market or the intraday market. The explanatory variables consist of monthly observations of global economic policy uncertainty ($GEPU_t$, see Davis (2016), Swedish (domestic) economic policy uncertainty ($SWEEPU_t$, see Armelius et al. (2017) and Nordpool system spot prices (P_t).

The Global Economic Policy Uncertainty (GEPU) index gauges economic policy uncertainty across major economies, influencing economic performance indicators and behaviours. Comprising three components – newspaper coverage, tax code expirations, and economic forecasts – the components create a normalised monthly index. The Swedish Economic Policy Uncertainty (SWEEPU) index, adopting a similar methodology, analyses articles from major Swedish newspapers for key economic and policy terms. The equity market volatility tracker monitors fluctuations in the CBOE volatility index (VIX) and S&P 500 return volatility (Baker et al., 2019). Despite offering valuable insights into economic policy uncertainty, these indices should not be perceived as infallible predictors of future conditions.

To control for inflation, system spot prices are deflated using CPI excluding energy (CPIF-XE), with the base year set to 1996 (collected 2022-06-13). See Appendix C for graphical presentations of the explanatory and control variables. The control variables consist of economic tendency in previous periods (ETI_{t-1}), market uncertainty (EMV_t) and previous levels of supplied electricity (Y_{t-1}^{PS}). The control variables are in this study considered as driving factors for electricity demand and previous levels of generated electricity.

2.2. Pre-estimation tests

All variables are tested for nonlinearity using a BDS test, and the majority display strong nonlinear characteristics, something also confirmed by the Jarque–Bera test (J–B). The power supply time series have also been tested for seasonal patterns (see Supplementary Material), and the GCQ analysis has been performed on both level series and seasonally adjusted series. Seasonal adjustments have been made by applying Census X-13 ARIMA-SEATS.[3] The series has been tested for stationarity by using the augmented the Dickey Fuller test (ADF, Dickey and Fuller, 1979)

[3] https://www.census.gov/data/software/x13as.html

Table 2
Unit root tests.

Variable name	ADF		PP	
	Level	FD	level	FD
Log level series				
Total power supply (Total)	−2.75*(12)	−7.94***(11)	−3.84***(24)	−19.43***(21)
Nuclear power supply (Nuclear)	−2,76*(12)	−7.28***(11)	−6.05***(20)	−34.18***(56)
Hydro power supply (Hydro)	−7.89***(3)	−11.26***(8)	−7.17***(6)	−33.59***(22)
Back pressure power supply (BPP)	−1.97(11)	−7.08***(12)	−3.68***(35)	−8.62***(111)
Industrial back pressure power supply (Ind BPP)	−1.43(12)	−6.03***(12)	−7.51***(2)	−30.06***(20)
Conventional thermal power supply (Conv)	−3.44**(4)	−15.20***(3)	−8.94***(10)	−85.43***(150)
Power imports (Imp)	−7.75***(0)	−12.34***(3)	−7.75***(0)	−50.27***(81)
Economic tendency indicator index (ETI)	−3.77***(1)	−14.51***(0)	−3.68***(7)	−14.43***(2)
Swedish EPU (SWEEPU)	−3.45**(4)	−13.78***(3)	−9.45***(9)	−62.12***(67)
Equity market volatility (EMV)	−7.60***(0)	−12.41***(3)	−7.52***(5)	−77.49***(178)
Global EPU (GEPU)	−2.94**(0)	−13.23***(2)	−5.39***(0)	−29.49***(32)
Nord Pool system spot price (P)	−3.14**(0)	−13.88***(1)	−3.24**(7)	−16.99***(4)
Seasonal adjusted series log level				
Total power supply (Total)	−6.50***(0)	16.8***(1)	−6.23***(5)	−70.76***(117)
Nuclear power supply (Nuclear)	−6.38***(0)	−13.84***(2)	−7.20***(7)	−29.03***(18)
Hydro power supply (Hydro)	−6.91***(0)	−22.3***(0)	−6.99***(6)	−29.17***(17)
Back pressure power supply (BPP)	−3.26**(2)	−17.36***(1)	−4.74***(1)	−95.44***(301)
Industrial back pressure power supply (Ind BPP)	−3.42*(2)	−17.31***(1)	−2.60*(6)	−28.13***(8)
Conventional thermal power supply (Conv)	−5.17***(1)	−12.81***(3)	−9.05***(10)	−40.50***(24)
Power imports (Imp)	−7.74***(0)	−16.4***(1)	−7.68***(4)	−52.71***(69)

Note: Augmented Dickey Fuller test, (lag) length is automatically decided, based on SIC. Maximum lags = 12. Philips–Perron test estimated with Bartlett kernel and automatic bandwidth selection by Newey–West. All series have been log-transformed. Power supply series have also been tested and seasonally adjusted (the logarithm of seasonally adjusted series). *p*-value ≤ .01(***). ≤.05(**). ≤ .1(*).

and the Phillips Perron test (PP, Phillips and Perron, 1988). The results in Table 2 show that the null hypothesis can be rejected at the 1% to 5% significance levels for many of the variables. However, as the null hypothesis cannot be rejected at the level for industrial back pressure power supply (seasonally adjusted), the analysis will only be performed with detrended series to acquire the necessary stationary properties required.

2.3. Granger causality in quantiles

Instead of focusing on a single part of the conditional distribution, the GCQ test evaluates nonlinear causalities and possible causal relations in conditional quantiles (Troster, 2018), in this case ($\tau = 0.1, 0.3, 0.5, 0.7, 0.9$), where *Unc* represent the uncertainty measures (independent variables) and *Ps* represent power supply series (dependent variables). The study tests for Granger causality in quantiles according to the following equations:

$$H_0^{\mathrm{Unc}\nRightarrow\mathrm{Ps}}: E\left\{1\left[\mathrm{PS}_t \le m\left(I_t^{\mathrm{Ps}}, \theta_0(\tau)\right)\right] I_t^{\mathrm{Ps}}, I_t^{Unc}\right\} = \tau, \text{ a.s. for all } \tau \in \mathcal{T} \quad (1)$$

against:

$$H_A^{\mathrm{Unc}\nRightarrow\mathrm{Ps}}: E\left\{1\left[\mathrm{PS}_t \le m\left(I_t^{\mathrm{Ps}}, \theta_0(\tau)\right)\right] I_t^{\mathrm{Ps}}, I_t^{Unc}\right\} \ne \tau, \text{ a.s. for some } \tau \in \mathcal{T} \quad (2)$$

According to Eqs. (1) and (2), an explanatory vector $I_t \equiv \left(I_t^{Ps}, I_t^{Unc}\right)$, does not Granger cause another series if previous values of the independent variable do not help to predict future dependent variable values (for all quantiles $\mathcal{T}$ in Eq. (1) and for some quantiles in Eq. (2)), where $I_t^{Ps} := (Ps_{t-1}, \ldots, Ps_{t-q})$ and $I_t^{Unc} := (Unc_{t-1}, \ldots, Unc_{t-q})$. Furthermore, $m\left(I_t^{\mathrm{Ps}}, \theta_0(\tau)\right)$ specifies the parametric model, where $Q_\tau^{Ps}(\cdot|I_t^{Ps})$ is the τ-conditional quantile.

A more detailed description of the GCQ test is provided in the supplementary material. For a full description, see Troster (2018).

2.4. Quantile regression

The QR analysis is used to analyse the dynamic relationship between independent and dependent variables (Koenker and Bassett, 1978). In this study, the multiple QR estimations, on both levels and for changes in power supply, capture the dynamics in the whole distribution. An ordinary least square (OLS) estimation is also presented in each figure in order to make comparisons between linear and nonlinear estimations. In Eq. (3), Y_τ^{PS} represents the dependent variables, constituting Swedish power sources, I_τ^i represents the explanatory and control variables, where the independent variables are uncertainty and spot price (SWEEPU, GEPU and P) and the control variables are lagged economic activity and market uncertainty (ETI_{t-1}, EMV and lagged dependent variable Y_{t-1}^{PS}), and τ indicates the studied conditional quantiles of Y_τ^{Ps}, which in this paper are $\tau = (0.1, 0.3, 0.5, 0.7, 0.9)$. The β_i determines the association between dependent and independent variables, and $\varepsilon_t(\tau)$ is the error term in considered quantile.

$$\begin{aligned} &Y_\tau^{Ps}\left(\tau | SWEEPU_t, GEPU_t, P_t, EMV_t, ETI_{t-1}, Y_{t-1}^{PS}\right) \\ &= c(\tau) + \beta_1(\tau) SWEEPU_t + \beta_2(\tau) GEPU_t + \beta_3(\tau) P_t \\ &\quad + \beta_4(\tau) EMV_t + \beta_5(\tau) ETI_{t-1} + \beta_6(\tau) Y_{t-1}^{PS} + \varepsilon_t(\tau) \end{aligned} \quad (3)$$

Quantile regressions are run in R using the quantreg package using the Barrodale and Roberts algorithm (Koenker and Bassett, 1978; Koenker and d'Orey, 1994), where 95% confidence intervals are estimated by wild bootstrapping methods with 1000 iterations. To control for multicollinearity, a variable inflation factor (VIF) test was performed on all independent variables used in the analysis. The highest uncentred VIF coefficient was 1.399, which

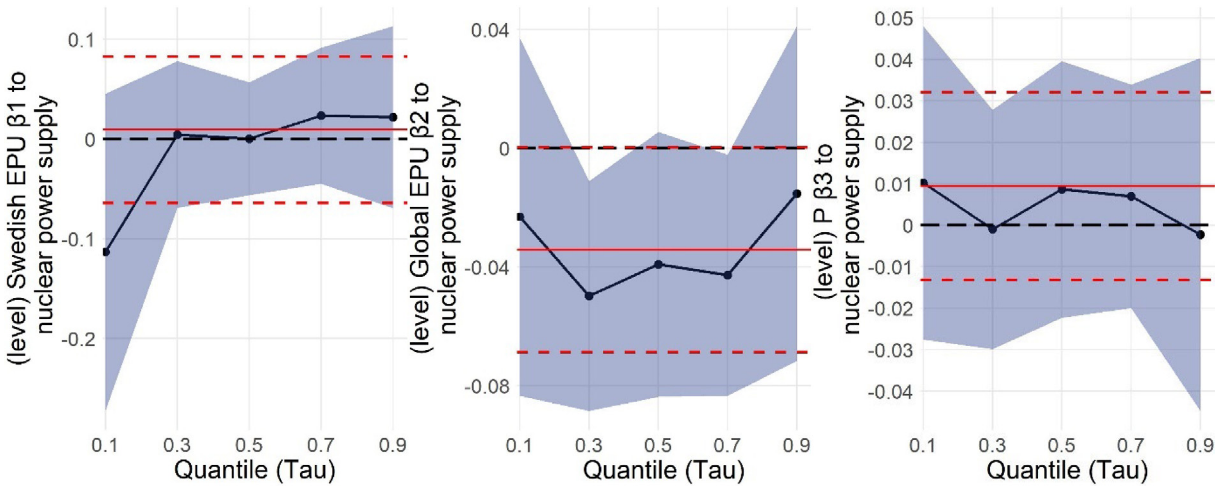

Fig. 3. Nuclear power supply. Log level series, where the QR estimations and confidence intervals = black line and grey area, OLS estimate and confidence intervals = red lines, and zero level = black dashed line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

indicates no multicollinearity (for details, see supplementary material).

3. Results

To infer Granger causality, all models ($\gamma = 1$ to 3) need to be significant at least at the 5% significance level. Significant GCQ results in seasonally adjusted series are a prerequisite for continued analysis through QR. Significance in all models are indicated by colouring table cells with p-values less than 5%. GCQ results are presented in tables and QR results in figures. In figures presenting the QR results, estimates are presented in black areas and confidence intervals in grey. Estimates for output levels should be interpreted as elasticities, representing the % of change in β_i given a 1% change in the explanatory variable (thus: $100 * (1.01^{\beta} - 1)$ percent change in Y_{τ}^{PS}). For the results in first differences of logarithmic variables, the interpretation is the logarithmic approximation of the actual changes. Estimates in first difference ($\Delta \ln$) should also be interpreted as $\beta_i * 100$ displays the % of change in Y_{τ}^{PS} given a 1% change in X_i in given quantile τ. A selection of GCQ results is presented in the article and full GCQ results can be found in supplementary materials.

3.1. Total electricity supply

The study finds no evidence to support any causal relationships between any of the independent variables and total supply of electricity (see Table S.4 in the supplementary material). The results are the same for both seasonally adjusted series as well as for series with seasonal effects (and for both power output levels and for changes in power output). This may indicate that the aggregate power supply is able to fulfil demand, given that electricity demand is considered inelastic in the short run (day-ahead and intra-day market) (Sensfuz et al., 2008). This result may also be contributed to the fact that total electricity supply includes renewable power (mainly wind power), and there can thus exist a merit order-effect on price and demand scheduling (Ciarreta et al., 2017; Clò et al., 2015).

3.2. Nuclear power supply

3.2.1. Quantile causality

Granger causality in quantiles results (Table S5, supplementary material) show that there is evidence of causal and directional relations between uncertainty, system spot prices and nuclear power supply. Controlling for seasonality, the pattern is accentuated for the results concerning power output levels as well as changes in power supply. The results show that both domestic (Swedish EPU) and global uncertainty (Global EPU) influences nuclear power supply at very high output levels [$\tau = 0.9$]. Additionally, global uncertainty and spot price also influence normal operating power output levels [$\tau = 0.5$]. Price and uncertainty impacts at normal operating conditions may be attributed to start-up and shutdown costs and competition between renewable and nuclear power on the electricity market (Mezősi et al., 2020).

3.2.2. Quantile regression

The results in Fig. 3 show both nonlinear and asymmetric responses. An increase in domestic uncertainty at very high levels of outputs leads to a minor increase in power supply. An increase in global uncertainty leads to decreases in power supply, and an increasing spot price leads to an increase in power supply.

The response in moderate increases of output levels could be considered consistent with nuclear power being optimised for constant base load power supply (kraftnät, 2019). Thus, nuclear power has to manage near normal operating situations, where the main tasks are stabilising frequency, voltage, and rotor angle. The generators in nuclear power plants are designed to give reactive power in normal operation (about one third of active power). Increasing domestic uncertainty seems to have little or marginal effect on output in normal operating conditions of power output. The relative sensitivity to global uncertainty may be related to international exports of electric power, where increasing transfer capacity between Nordic and European countries can increases the risk of rotor angle instability (kraftnät, 2019).

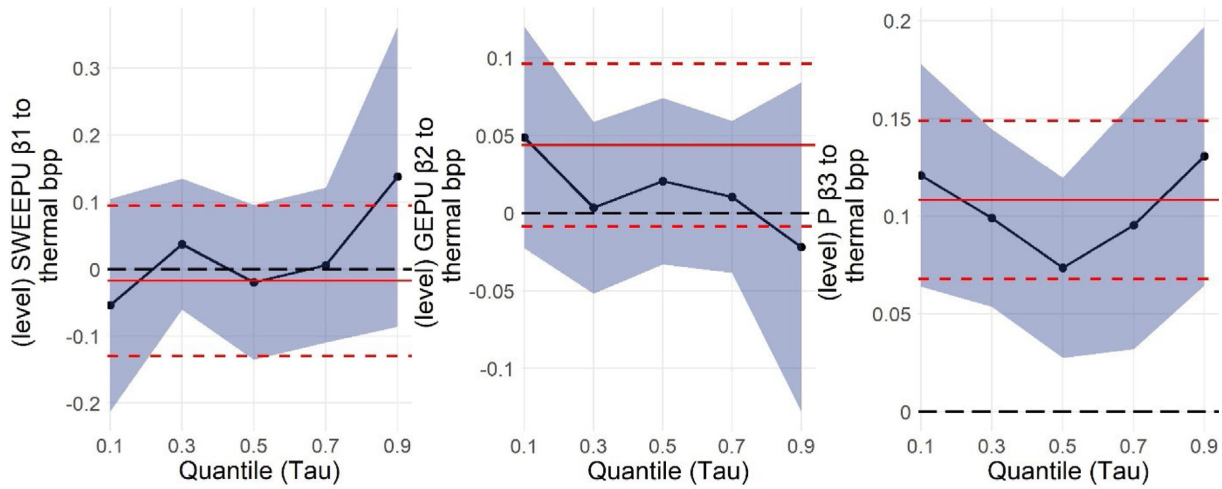

Fig. 4. Back pressure power supply thermal plants Log level series, where the QR estimations and confidence intervals = black line and grey area, OLS estimate and confidence intervals = red lines, and zero level = black dashed line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.3. Hydro power

The results provide no clear evidence to support any Granger causality relationships between any of the independent variables and hydro power supply (Table S6, supplementary material). Adjusting for seasonal effects does not change the results. The relatively low variable cost makes hydro power a base load source of electricity; however, it also serves as the main source for balancing the power grid. The general interpretation is that hydro power supply is quite stable with regards to uncertainty and prices. Variations in hydropower supply mainly come from seasonal effects and precipitation, leading to varying relative filling levels of hydro power reservoirs (Podewski and Weber, 2021).

3.4. Back pressure power generation thermal plants

3.4.1. Quantile causality

The results (Table S7, supplementary material) indicate causal and directional relations between uncertainty, system spot prices and back pressure power supply, both for series with seasonal effects and seasonally adjusted power supply series. Domestic and global uncertainty, as well as system spot prices, seem to influence back pressure power at very low levels [$\tau = 0.1$], moderately low levels [$\tau = 0.3$] and moderately high levels of output [$\tau = 0.7$].

3.4.2. Quantile regression

The results in Fig. 4 show that an increase in spot price seems to generate positive feedback signals for all power output situations. At low levels of output, domestic uncertainty seems to generate negative feedback signals, decreasing power supply, while global uncertainty seems instead to increase power output.

Thermal plants in Sweden have varying cost structures, utilising different fuels (waste, oil, biomass, etc.) and different turbines, or combinations of turbines, for power generation (gas turbine and steam turbine). Furthermore, the decision to provide electric power to the market is often linked to local conditions related to district heating, something that could explain some of the varying changes in output (Felten, 2020). In 2021, the thermal power generation capacity installed in 113 thermal plants was around 4000 MW, with the potential to supply up to around 17 TWh to the market (Bioenergitidningen, 2021). However, the real power generation output was considerably lower as thermal electricity power production is highly dependent on electricity prices (Bioenergitidningen, 2021). The European energy crisis in 2022 has demonstrated the value of excess power generating capacity and the need for rapid increases in dispatchable power supply. And CHPs helps balancing electricity and district heating (Lund and Mathiesen, 2009), it can play an important role in developing stable sector coupling initiatives. Given the potential for increasing back pressure power, an understanding of supply dynamics can be vital for increasing electrical power supply (Toke and Fragaki, 2008).

3.5. Industrial back pressure power generation

3.5.1. Quantile causality

The results (Table B5, supplementary material), including seasonal effects, provide no evidence to support any Granger causality relationships. However, adjusting for the seasonal effects reveals that global uncertainty and spot prices influence industrial back pressure power supply in times of very large negative changes in output [$\tau = 0.1$] and moderately positive changes in output [$\tau = 0.7$].

3.5.2. Quantile regression changes

The results presented in Fig. 5 show strong nonlinear and asymmetric power output responses to changes in global uncertainty and spot prices. An increase in global uncertainty, in times of decreases in output [$\tau = 0.1$], leads to further decreases. On the other hand, rising global uncertainty in situations of increasing output [$\tau = 0.7$] leads to further increasing changes. Increasing spot price in times of very large decreases in output [$\tau = 0.1$] have almost no effect on output. However, a rise in spot price in times of increasing power output [$\tau = 0.7$] leads to further increases.

An increase in global uncertainty seems to generate reinforcing feedback signals that are negative in situations of decreasing output and increasing in situations of increasing power output.

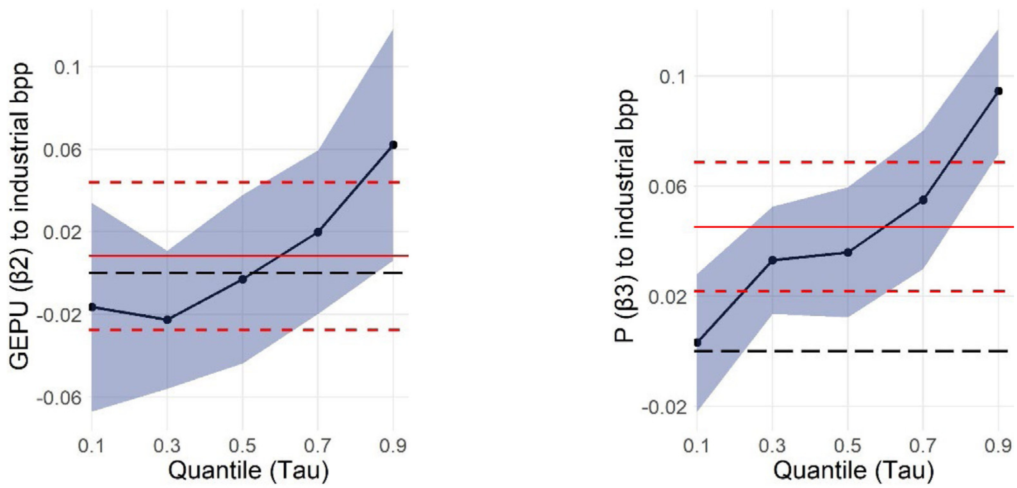

Fig. 5. Industrial back pressure power (First differences of log series, where the QR estimations and confidence intervals = black lines and grey area and OLS estimate and confidence intervals = red lines). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

An increase in spot price seems to generate a reinforcing feedback signal that amplifies over the distribution. One of the main reasons for industrially generated electric power is to offset, or altogether replace, electricity use delivered through the grid (Irungu et al., 2017; Pariasamy et al., 2022). Alternatively, operational variability generates surplus electric power that can in turn be exported to the grid. In this context, the influence of system spot prices on industrially generated power are in line with the economic rationale. The influence on global uncertainty displays an effect on output in the upper quantiles similar to that of spot prices, while in the lower quantiles it has the opposite effect. This finding could be related to the fact that the number of annual operating hours is a critical factor for providing surplus electricity to the grid (Shabbir and Mirzaeian, 2016). Since 2008, Sweden exports around half of its total annual GDP (The Swedish Riksbank, 1982-2021), where the majority of exports goes to the European market. Therefore, studying exogenous shocks to the system, in this case uncertainty impacts, can be vital for assessing the dynamic structure of industrially generated electricity. Also, in order to enable any meaningful analysis of potential effects from system integration and sector coupling, with regards to industrially generated electrical power, systems analysis of local conditions and the study of idiosyncratic factors will likely be necessary. Not only because industrial plants differ in technology, economic lifetime and the layout of the industrial processes and the respective product end markets (Svensson et al., 2019), but also in relation to individual responses to external shocks, e.g., uncertainty impacts.

3.6. Conventional thermal condensing power generation

3.6.1. Quantile causality

The results (Table B6, supplementary material) indicate a causal relation between dependent and independent variables. Adjusting the series for seasonal effects highlights a strong causal influence from all independent variables in low [$\tau = 0.1$] to moderately low [$\tau = 0.3$] and high levels of power supply [$\tau = 0.7$].

3.6.2. Quantile regression

The results in Fig. 6 indicate highly nonlinear responses to uncertainty and spot prices. An increase in domestic uncertainty leads to further decreases in power supply at very low levels of power output [$\tau = 0.1$] and high levels of output [$\tau = 0.7$]. At moderately low levels of output [$\tau = 0.3$], rises in uncertainty seem to have a stabilising influence on output. An increase in global uncertainty seems to have the opposite influence, where an increase at very low power output levels [$\tau = 0.3$] leads to a significant increase in power supply. At moderately low and high levels of output, rising global uncertainty also seems to lead to increases in power supply, but not as large as at very low output levels. An increase in spot price has a generally positive influence on power output.

Increasing domestic uncertainty seems to generate mainly negative feedback signals, decreasing both power output levels and changes. Global uncertainty, on the other hand, seems to generate increases in power output but at a decreasing change rate. Increasing spot prices generates increases in both output levels and in changes. Conventional power generation in Sweden is mainly, if not exclusively, used as reserve power. However, given the recent global circumstances, these powerplants will likely play an important role in a near future for the Swedish energy system.

3.7. Power imports

3.7.1. Quantile causality

The GCQ results (Table S10, supplementary material), after adjusting for seasonal effects, indicate causal relations between power imports, domestic and global uncertainty [$\tau = 0.1$-0.3 and 0.9] and spot prices [$\tau = 0.3$ and 0.9].

3.7.2. Quantile regression

The results in Fig. 7 display strong nonlinear responses to uncertainty and spot prices, especially at very low levels of power imports [$\tau = 0.1$]. An increase in domestic uncertainty at very low import levels [$\tau = 0.3$] leads to increases in power imports. A rise in domestic uncertainty at very high import levels instead leads to decreases in power imports. Increases in global uncertainty has a general negative influence on power imports, although an increase in global uncertainty at very low import levels leads to a sharp further decrease in power imports. Rising spot price, on the other hand, leads to an increase in power imports, especially at low import levels [$\tau = 0.1$].

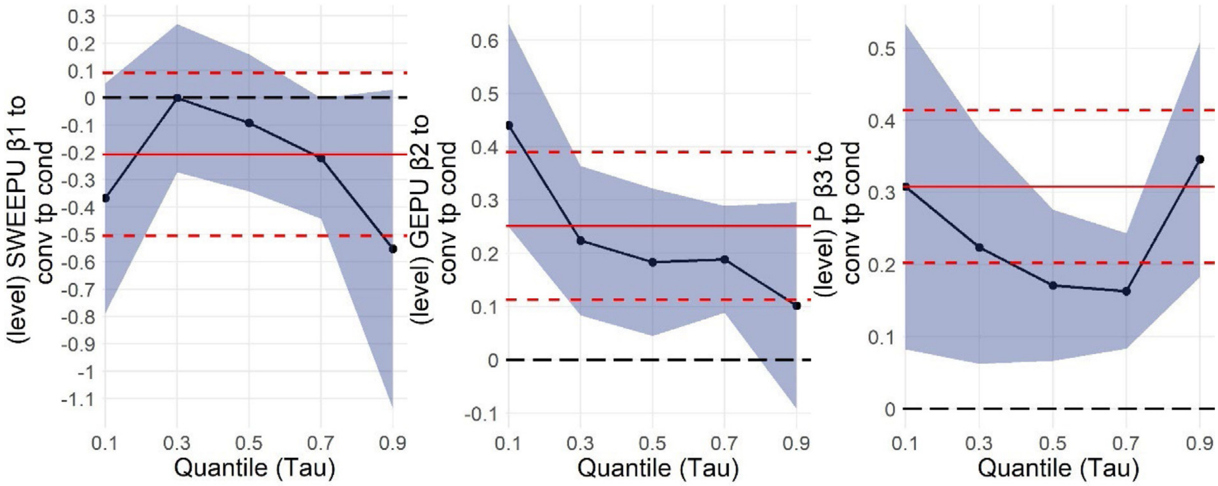

Fig. 6. Conventional condensing power (Log level series, where the QR estimations and confidence intervals = black lines and grey area and OLS estimate and confidence intervals = red lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

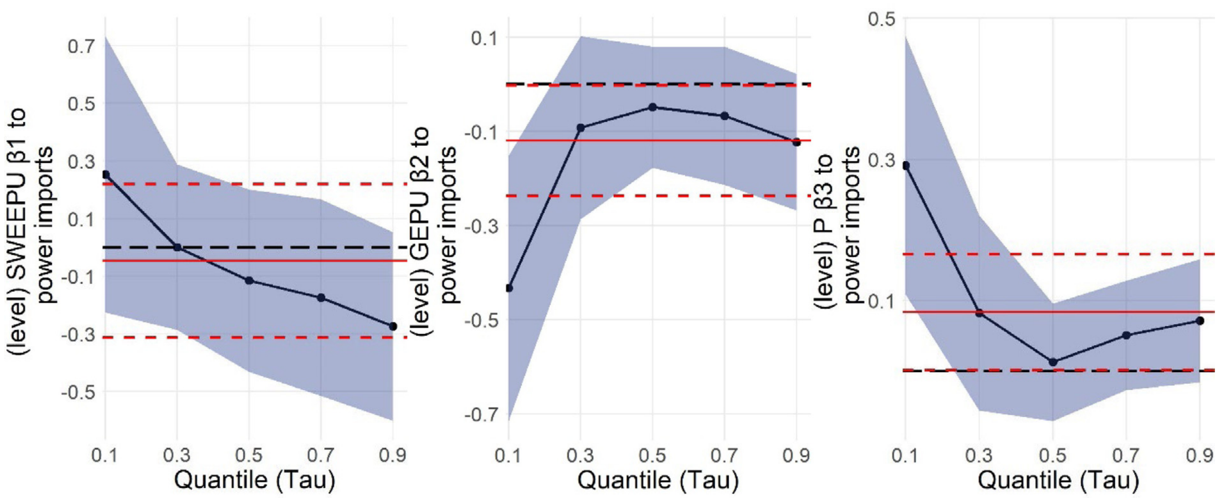

Fig. 7. Power imports (Log level series, where the QR estimations and confidence intervals = black lines and grey area and OLS estimate and confidence intervals = red lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Global uncertainty seems to be generating only negative feedback compared to domestic uncertainty, especially at very low levels of power import levels. Domestic uncertainty, in comparison, generates positive feedback signals at very low import levels and negative feedback signals at very high import levels. Power imports are a vital function for the Swedish power system, and the need for power imports may arise for various reasons. Power shortage can be a consequence of limited generating capacity in parts of Sweden where the demand is high. For example, due to high intermittent (weather dependent renewable wind and solar power) generation capacity in combination with a limited net transfer capacity between regions, there can be situations with shortages in electricity supply and excess supply at the same time, albeit in different regions.

4. Discussion

By studying dispatchable power supply responses to changes in uncertainty, this paper finds large variations in supply dynamics between power sources.

This indicates that uncertainties persist on several system levels and that the nature of the uncertainties are different for each power source. System levels in this context refers to, for example, power supply on an aggregated national system level, power supply from a specific power source (system component level) or local systems (micro or meso system levels).

Uncertainties in previous literature are mainly related to the intermittent nature of renewable power generation and the technical factors for system stability, such as power system failures and loss of generating units (Singh et al., 2022). In contrast, this paper studies power system behaviour by analysing uncertainties originating from outside the system and different sources (domestic and global uncertainties) and the information-feedback responses generated by the system.

As stated previously, the development of efficient and sustainable systems will occur at the local or regional level (Korhonen et al., 2018). Thus, the detailed understanding of the uncertainties influence on electric power sources and supply dynamics, which this study provides, can serve as invaluable tools for analysing the context of uncertainty impacts (Walker et al., 2022), and of various interdependencies in a highly electrified and interconnected system (Ilo and Schultis, 2022; Lund et al., 2017). Market uncertainties influence supply–demand balance, regulatory changes, and competition, for example affecting revenue streams of power plants (Timmons et al., 2014). Global economic policy uncertainties, like emission regulations and subsidies, alter the cost-effectiveness of different power sources and potentially stall investment (Polzin and Sanders, 2020). Electricity price fluctuations, impacted by weather conditions and other supply dynamics, can differently affect the integration of new power sources (Krečar and Gubina, 2020). Uncertainties can influence the technological development in power generation, energy storage, and efficiency can redefine the competitiveness of power sources (Swann, 2014) and energy return on investment (EROI) (Oosterom and Hall, 2022; Yang et al., 2022). Hence, an understanding of electricity behaviour is critical in strategic decision-making regarding power generation, new technology investments, and policy formulation. This knowledge could be important from a strategic perspective, in both the short and in the long run for the transmission system operator (TSO) preserving the grid frequency and balancing markets in a specific location (Javanshir et al., 2023).

This study offers valuable monthly insights into uncertainty and the Swedish power system. The results are also highly relevant within the context of the Nordic perspective, where several countries, each with a unique mix of energy sources and technologies, are interconnected (Svenska kraftnät, 2023; Weihs et al., 2020). However, in order to gain even deeper understanding, high frequency data could open up for more detailed findings. High frequency data in this case refer to daily or hourly data. For a more detailed understanding of how, for example, the industrial and transportation sectors may behave when connected, minute- or even second-based data may be a preferred time scale. Another limitation is the data content. As the data provided are made to be anonymous, there is lack of specificity and understanding of local features and effects. Additionally, not all power supply data are collected and presented in the statistical compilation provided by statistics Sweden. However, the omitted power supply is minuscule and is not considered a major issue for the analysis. These limitations can be addressed somewhat by using various data sets of sectors and sources, something that should be pursued in future research. Even though the QGC and QR methods complement each other and are considered well established, machine learning and other IA methods could be of great value in the future. On the other hand, QGC and QR are transparent with regards to complications of non-transparent AI problems.

The market seems to clear on an aggregate level; however, the analysis shows the complexity of the system when considering the power sources. As industry is one of the key sectors when it comes to creating a sustainable future; hence, further studies of energy synergies in industrial production are needed. Likewise, future analysis needs to incorporate demand dynamics from the housing and services sector as it represents the largest share of electric power demand. Thus, a comprehensive systems analysis will have to contain relations both between and within supply side and demand side components and sectors, analysed on appropriate system levels.

5. Conclusion

Highly integrated systems and sectors pose challenges when it comes to understanding system dynamics and impacts from unforeseen events, and how to best utilise electric power sources. By applying quantile-based methods, this study has examined nonlinear relations regarding how uncertainty and spot prices influence electric power supply in Sweden. The findings show that, on an aggregated level, power supply does not seem to be sensitive to changes in uncertainty and spot price. However studying specific power sources reveals more complex dynamics. The results show that studying responses to uncertainty can be useful not only when forecasting electric power supply in a highly integrated energy-industrial systems but also planning and synchronising industrial production processes. The studied power sources are influenced differently depending on the type of uncertainty (global or domestic), and the responses to uncertainty are highly nonlinear. This means that linear models (based on mean values) do not capture the dynamics of how uncertainty impacts power supply. The causal relations (causal patterns) seem to be both power source specific, and specific to type of uncertainty. This means that power generating sources are susceptible to uncertainty at specific market conditions and depend on the type of generation sources being considered. The findings in this study indicate that actors on the supply side act differently with respect to global and domestic uncertainty, and that this behaviour influences both power supply levels and changes in supply. Thus, global uncertainty seems to be the dominant form of uncertainty for Swedish power supply compared to domestic uncertainty.

An implication of the results of this study is that, when creating resource efficient systems, decision makers and system designers should tailor policies for specific sectors and system behaviour based on idiosyncratic circumstances, such as the reactions to different types of uncertainty highlighted in this study. Likewise, in order for there to be any efficient utilisation of surplus electrical power or power exchanges between sectors, system behaviour specific to power sources will have to be considered. Future studies should focus on a further examination of local conditions and the underlying reasons for the variations in responses to uncertainty. Furthermore, this study also highlights the need for high frequency data (minutes or hourly data) when analysing the potential for sector coupling and system integration. This is especially important in order to understand rapid changes in power supply and power demand in the short and very short run.

CRediT authorship contribution statement

Christoffer Wadström: Conceptualisation, Visualisations, Formal analysis, Writing – original draft, Writing – review & editing. **Maria Johansson:** Supervision, Funding acquisition. **Gazi Salah Uddin:** Validation, Supervision.

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.

Data availability

Data will be made available on request.

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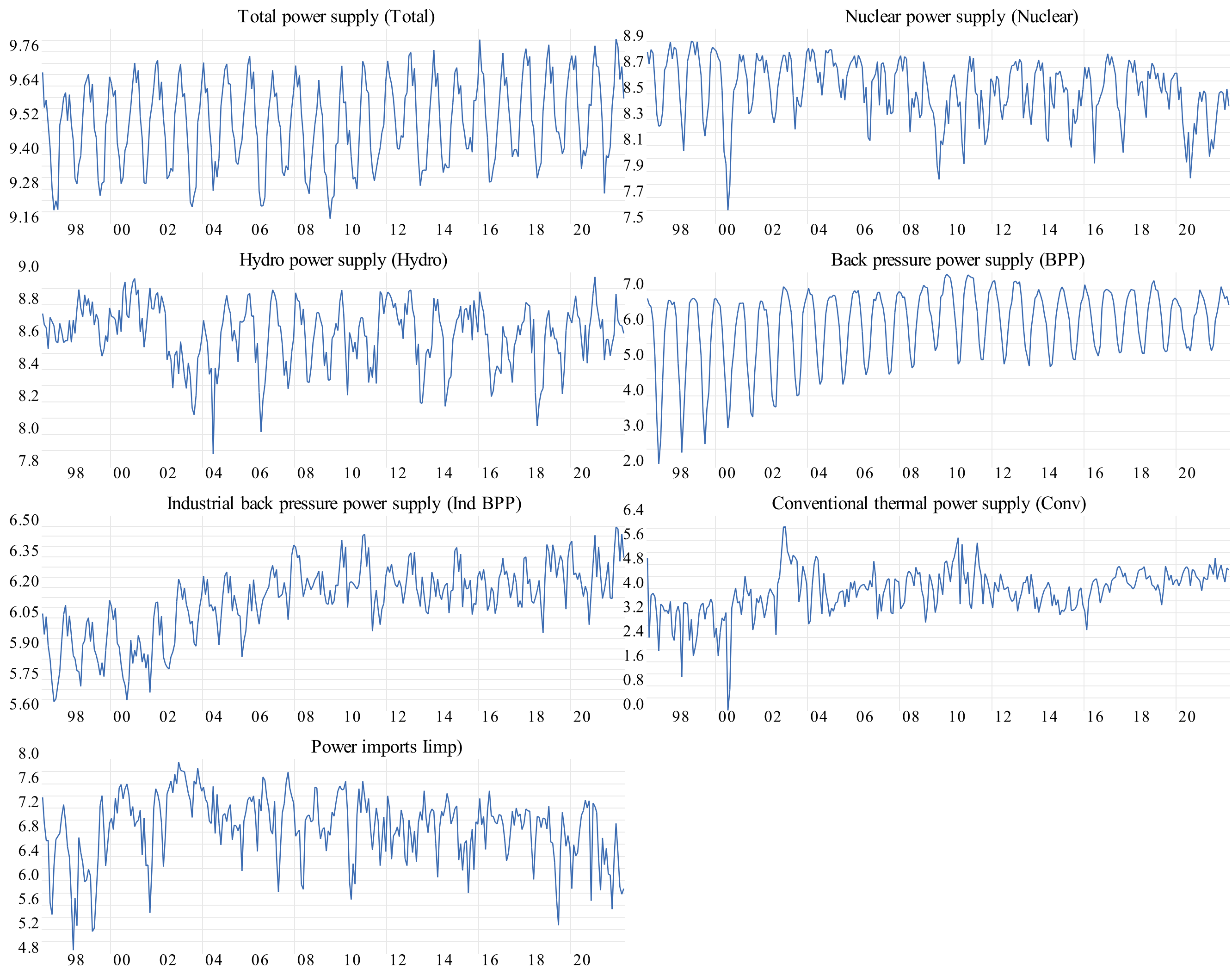
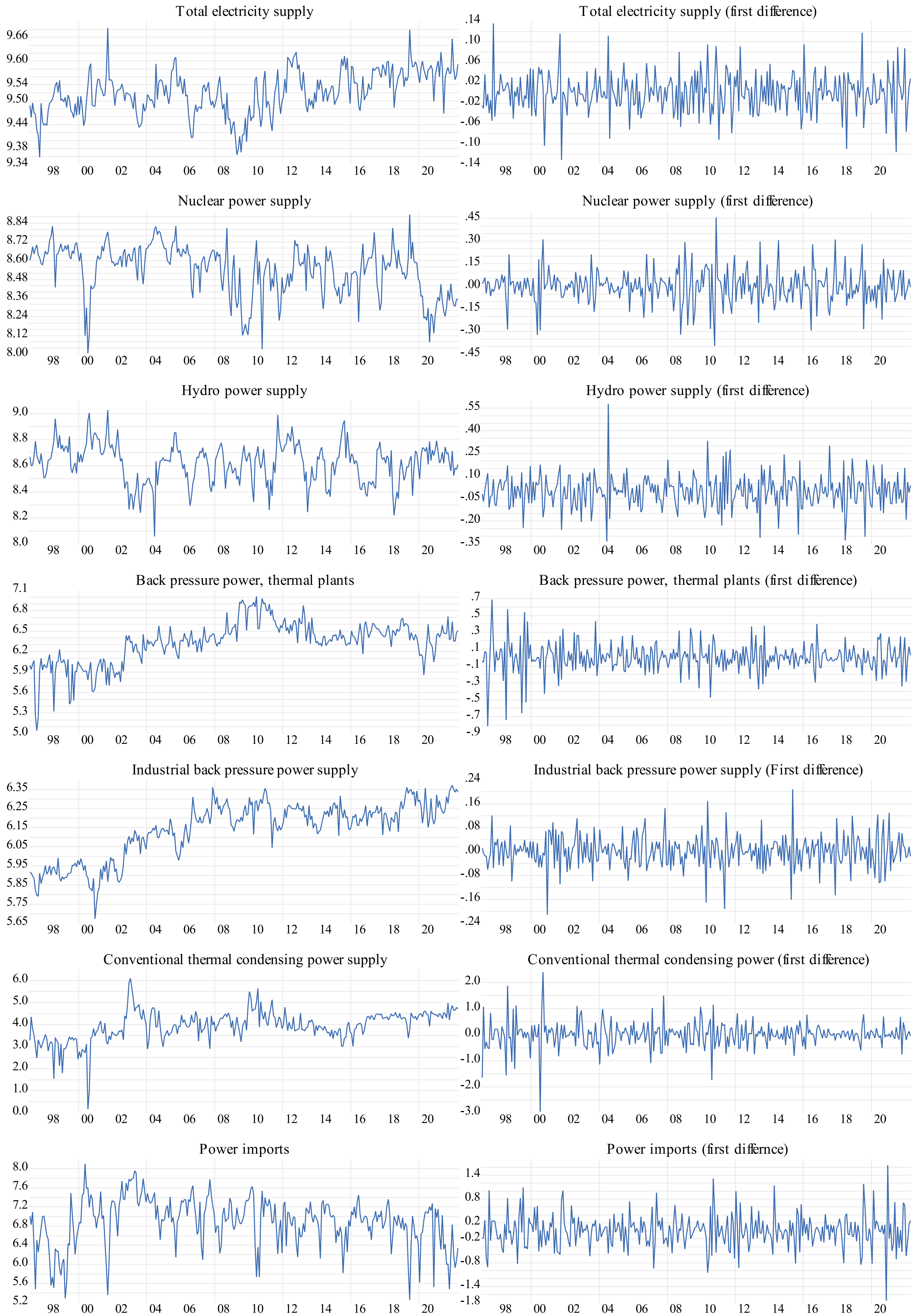
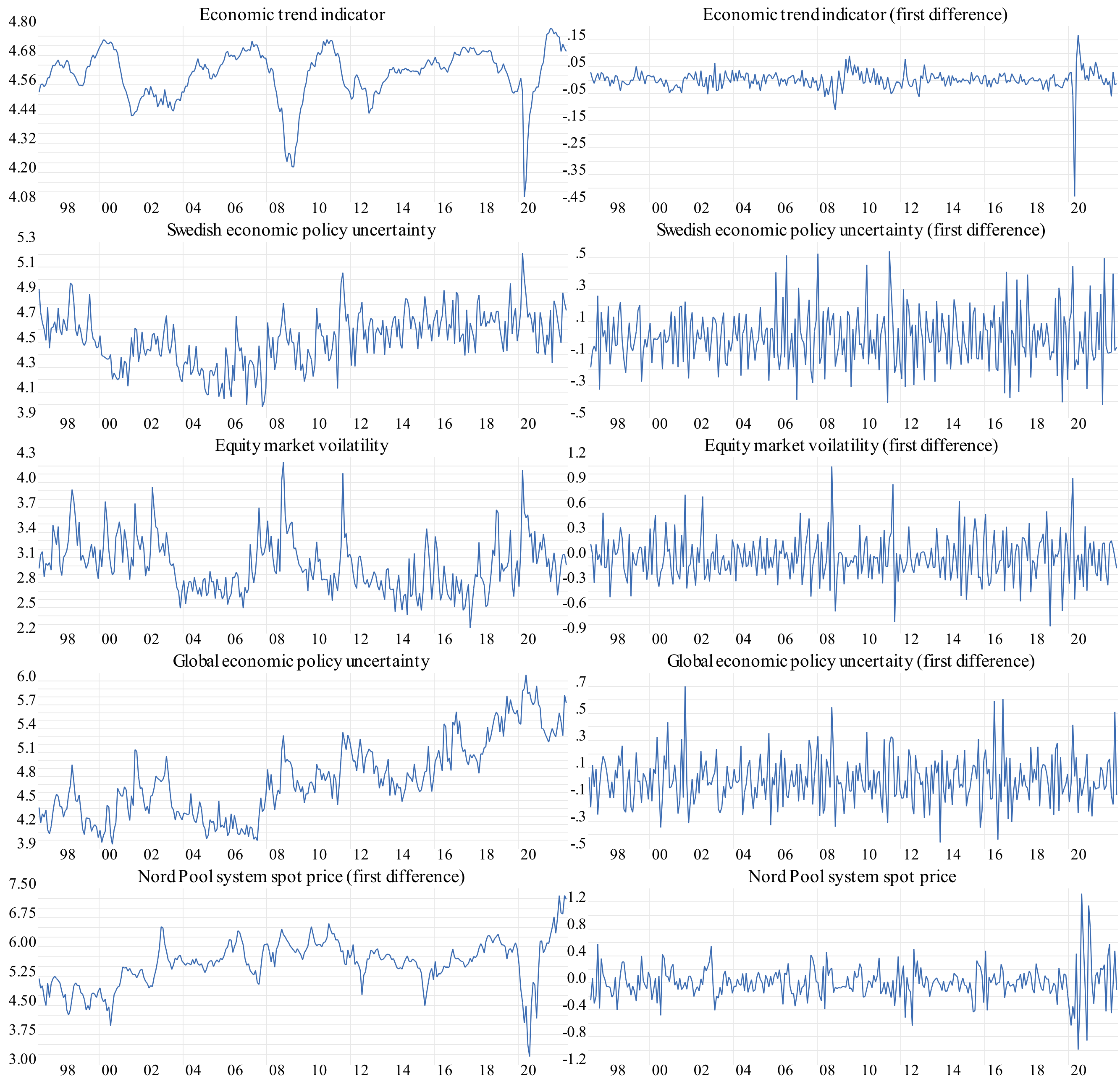
Appendix A. Dependent variables



Appendix B. Seasonal adjusted dependent variables


Total electricity supply
9.66
9.60
9.54
9.50
9.44
9.38
9.34
Total electricity supply (first difference)
.14
.10
.06
.02
-.02
-.06
-.10
-.14
Nuclear power supply
8.84
8.72
8.60
8.48
8.36
8.24
8.12
8.00
Nuclear power supply (first difference)
.45
.30
.15
.00
-.15
-.30
-.45
Hydro power supply
9.0
8.8
8.6
8.4
8.2
8.0
Hydro power supply (first difference)
.55
.40
.25
.10
-.05
-.20
-.35
Back pressure power, thermal plants
7.1
6.8
6.5
6.2
5.9
5.6
5.3
5.0
Back pressure power, thermal plants (first difference)
.7
.5
.3
.1
-.1
-.3
-.5
-.7
-.9
Industrial back pressure power supply
6.35
6.25
6.15
6.05
5.95
5.85
5.75
5.65
Industrial back pressure power supply (First difference)
.24
.16
.08
.00
-.08
-.16
-.24
Conventional thermal condensing power supply
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Conventional thermal condensing power (first difference)
2.0
1.0
0.0
-1.0
-2.0
-3.0
Power imports
8.0
7.6
7.2
6.8
6.4
6.0
5.6
5.2
Power imports (first differnce)
1.4
0.8
0.2
-0.2
-0.8
-1.4
-1.8
98 00 02 04 06 08 10 12 14 16 18 20

Appendix C. Explanatory and control variables



Appendix D. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.egyr.2023.07.049.

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