EFFECTS OF INCREASING WIND ENERGY SHARE IN THE GERMAN ELECTRICITY SECTOR ON THE EUROPEAN STEEL MARKET

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Abstract

The effects of an increased material demand resulting from the continuously growing deployment of renewable energy technologies on the raw material prices has not been investigated in detail. This paper proposes a general framework of an interdisciplinary approach to combine the material demand analysis with economic impacts. For the application of this approach, the steel demand in Germany is exemplarily chosen to be analyzed. Based on current market situation and energy scenarios, this paper discusses the development of wind turbine technologies in Germany and determines the required total steel demand for their deployment. In order to investigate the corresponding implications on the material prices, a vector auto regression and impulse response function is conducted. Results show that the additional demand from the German wind energy sector is minimal compared to the increase in total steel demand, thus only having a limited impact on the steel price. Further works is highly recommended to apply these approaches to determine the total material demand of other energy technologies within an energy system and its economic impacts as a whole.

1. Introduction

The German government has set goals to increase the share of renewable energy in the electricity supply, among others to 35 % by 2020 and 80 % by no later than 2050 [1]. Several studies have been published to prove the technical viability of a future energy system with high share of renewables in Germany [2,3]. Though there are many ways of achieving this, these studies share the common fact that wind energy will have the largest share in the German electricity production in the future. According to studies such as [2] and [4], the cumulative installed capacity of wind turbines is expected to be somewhere between 147 GW and 285 GW in 2050 if a 100 % renewable energy system is to be achieved.

Specific material properties are essential for a variety of future technologies, particularly the renewable energy technologies. Under the influence of the strong market dynamics and technological advancements, the number of intensively used materials has massively increased [5]. If left unchecked, the increasing demand in renewable energy technologies might lead to problems such as supply bottlenecks or price instabilities. Despite increasing numbers of studies that aim to investigate the resource demand due to the energy transformation process, the corresponding economic implications are often being overlooked. Therefore, we propose and analyze an approach to combine raw material demand analysis of an energy technology and econometric methods in order to investigate the economic effects of increasing raw material demand due to the energy transformation process.

The aim of the paper is twofold. Firstly to estimate the total steel demand to fulfill the development of the Germany wind energy sector based on existing energy scenarios. Secondly, a general framework of an interdisciplinary approach of combining the material demand with an economic analysis is presented and exemplarily applied on the steel demand. Steel is selected as a suitable material to be analyzed since it is the main component of a wind turbine, reaching more than 80% of its weight [6–8]. The evolution and the interdependencies between price and demand of steel as well as several other fundamental micro- and macroeconomic factors will be investigated via a simple and transparent vector auto regression (VAR) model [9]. As mentioned in [10], the simplicity of a VAR model enables the robustness and the sensitiveness of the results to be determined via parameter variations. Through an impulse response function (IRF), see [11], the future development of the steel price will be forecasted and analyzed.

2. Literature review

A large number of studies regarding the required material demand for the energy transformation process focus on one particular technology; for example [12] and [13] investigated the total material demand for the development of photovoltaics. Estimates presented by [14] shows that a bottleneck in the supply of Tellurium in the photovoltaic industry can be expected as early as 2025, if the thin film modules were to further develop as how they have in the past. In terms of wind turbines, [15] determined the material demand in Germany and identified a risk in the Neodymium supply. Other studies such as [16] and [17] investigated the demand of relevant critical materials such as rare earth elements (REE) in the manufacturing of various renewable energy technologies within an energy system. Despite the increasing number of studies investigating material demand of energy technologies, the estimated demand is always compared to the current availability of the investigated material in order to determine possible bottlenecks, with the economic implications of the increase in demand being overlooked. In the field of economics, studies show that additional demand of a commodity will generally lead to higher resource prices [18,19]. In some cases, an increase in demand of a single considerably large industrial consumer can lead to the higher commodity prices [20,21]. With Germany being the leading actor of renewable energy systems in Europe, the economic effects of the increase in demand due to the deployment of renewable energies cannot be neglected.

The economic effects can be investigated by analyzing the short and middle-term effects on the price of a commodity due to the changing demand. There are generally two ways of forecasting prices or any other microeconomic properties of metals: the intensity of use approach and the econometric method [22]. The former approach started to gain attention after the publication of [23] to forecast the material requirements primarily in the United States in 2000. As applied by [23] and [24], this approach assumes that the intensity of use and per capita income typically have an inverted U-shape -the so called Kuznets curve- relationship. This approach goes by the hypothesis that as a nation undergoes industrialization, the source of economy shifts towards service and thus reducing the demand for material intensive goods. [25] for example, proposed a model to examine the potential Kuznets relationship between long-term steel demand and economic development, which was later expanded to incorporate macroeconomic variables by [26] to estimate the future demand of metals including steel in China. However, the intensity of use approach has remained a less common approach in forecasting microeconomic variables at the benefit of the econometric approach.

As mentioned in [27], the econometrics approach provides insight on long-term cause and effect relationship between variables by considering short term dynamics via lags on variables. The most widely used and proven to be very efficient in describing dynamic behavior of economic time series is the vector auto regression (VAR) approach [28]. An important advantage of VAR is that a specification of exogenous variables over the forecast period is not compulsory. VAR models do not embody economic theory in the way that structural economic models do. However, they impose restrictions on the data, which are based on economic reasoning [22]. As an example of the application of VAR models, the authors in [29] investigated several variables that can improve the predictability of commodity price volatility and concluded that multivariate approaches via VAR can indeed improve price predictability. In [30] the authors determined the impact of macroeconomic influences on LME metal price fluctuations using dynamic factor analysis. Another interesting publication which share similar idea with our approach is [31], where the authors examined the effects on the Turkish interest rate, domestic spot gold and silver price by the world oil price and found that that the oil price has no predictive power over the aforementioned local economic factors in Turkey. Impulse response functions and error variance decomposition are tools to analyze the response of the VAR model to an innovation in one of the variables in the model [32]. This approach has been applied, for example in [33] and [34], to investigate the effects of oil price shocks on the demand and supply in various industries. In [35], the authors used VAR model and impulse response functions to show that federal fund shocks can be a good predictor of economic outputs.

By combining the proven approaches available in the literature, the main contribution of this paper is the general framework of combining raw material demand analysis of an energy technology and econometric methods including the impulse response functions in order to analyze the effects of increasing share of renewable energies in the energy system on the raw material price. To the best knowledge of the authors, there is no published paper in this context so far.

3. Conceptual framework and methodology

The proposed framework contains two main parts, namely the (I) estimation of total steel demand from wind turbines as well as the (II) economic implications addressed via VAR. In order to achieve the former goal, four aspects of wind turbines have to be considered; the steel composition, current and future market shares of turbine components, lifespan as well as the annual installed capacity of wind turbines. Once the annual steel demand is determined, a VAR model is set up and an IRF analysis is conducted to determine the behavior of the annual steel price due to corresponding demand.

3.1. Steel composition

In this paper, the most common designs in the wind energy sector in Germany, namely horizontal axis design, lift-based, with a three blades rotor and variable speed generator are considered. The generator type stands out as the most important factor that decides the material composition of a wind turbine. The six currently most commonly used wind energy conversion system types are listed in table 1. The total steel demand of current wind turbines can be estimated by determining the steel composition in rotor, nacelle, tower and foundation. Available life cycle (LCA) reports, as listed in table 5, are used as the basis in obtaining the compositions of raw steel. In terms of tower, both steel and concrete towers are considered since a concrete tower is actually composed of two thirds of prefabricated concrete segments and one segment of steel sections [36]. The steel compositions of different technologies with respect to their components are shown in table 2.

Table 1: Types of wind energy conversion systems considered in this paper

Drive train systems	*Doubly-Fed Induction Generator*	*Electrically-Excited Synchronous Generator-Direct-Drive*	*Permanent Magnet Synchronous Generator – High Speed*	*Permanent Magnet Synchronous Generator-Middle Speed*	*Permanent Magnet Synchronous Generator-Direct-Drive*	*Squirrel Cage Induction Generator Variable Speed*
Acronyms	DFIG	EESG-DD	PMSG-HS	PMSH-MS	PMSG-DD	SCIG
Type of generators	Induction	Synchronous	Synchronous	Synchronous	Synchronous	Induction
Type of excitation	Electrical	Electrical	Permanent Magnet	Permanent Magnet	Permanent Magnet	Electrical
Type of gearbox	3-stage	-	3-stage	1-stage	-	3-stage
Converter	Partial-scale	Full-scale	Full-scale	Full-scale	Full-scale	Full-scale
Examples of manufacturers	Nordex, GE, Gamesa	Enercon	Vestas	Areva	Siemens, Vensys	Vestas, Senvion, Siemens

Table 2: Steel share in each wind turbine component according to their respective types

	Rotor	*Nacelle*					*Tower*	
		DFIG	*EESG-DD*	*PMSG-HS/MS*	*PMSG-DD*	*SCIG*	*Steel*	*Concrete*
Steel share [%]	17.4	46.8	30.7	39.1	30.7	42.5	93.4	11.0

In terms of the foundation for offshore turbines, the most common foundation types in the German seas are the monopile, the jacket and the tripod/tripile. Their respective steel compositions are obtained from [37–39]. As for future potential floating foundations, only the tension-leg-buoy (TLB) is retained from [38], which is the design with least intensive steel consumption and lowest levelized cost of electricity [40], for future potential floating foundations. For onshore turbines, only the most common flat foundation type is considered.

Table 3: Steel share of wind turbine foundations

Foundation type	*Flat*	*Monopile*	*Tripod*	*Jacket*	*Semi-submersible*	*Tension-Leg-Buoy*
Steel share [%]	4.5	97.0	60.8	83.2	91.4	84.8

For the determination of the masses of the rotor, nacelle, tower and foundation of future wind turbines, the upscaling approach as proposed by [37] is used. Commonly used to estimate properties in relation to the size when no data are available, this method has been applied by [41–44] in order to analyze the increase in mass of future turbine designs. The coefficients for the upscaling of all wind turbine components, based on studies and manufacturer sheets listed in table 6, are provided in Appendix A.

3.2. Market share of towers and foundations

The market share of towers are determined based on [15]. Concrete towers are known to be more effective from 100 m height onwards, be it economically, mechanically as well as in terms of transportation regulations [45,46]. It is therefore assumed that it will gain market shares in the future. Concerning the foundation of onshore turbines, only the current conventional design with a flat concrete slab is considered. The long realization phase of offshore wind parks in Germany enables the planned foundation up to 2019 to be known exactly and included in the calculations in this paper. From 2020 to 2035, assumptions are made based on the average water depth of the North and Baltic sea [47,48] and the geographic planning of grid connections [49]. Currently still in the development phase, the floating foundations will gain market importance as construction sites gradually shift towards greater water depths in the North Sea from 2035 onwards. The complete assumptions on market share development of the towers and offshore foundations are shown in Appendix B: Table B1 and B2.

3.3. Lifespan of wind turbines

The life span of a wind turbine is generally assumed to be 20 years [50]. In studies such as [51] and [52], the total amount of capacity installed will be discarded after the life span of that technology. This method is known as the simultaneous exit function and has been criticized by several studies, further suggesting that a Weibull distribution, as shown in equation 1, is a better representation of the lifespan of a technology [53].

$$f(t, \lambda, k) = \lambda k (\lambda t)^{k-1} e^{-(\lambda t)^k} \tag{1}$$

Where t represents the lifespan in years, k the shape parameter and λ the scale parameter. The only study in the literature known to the authors having modelled the life span of a wind turbine according to a Weibull distribution is [15]. This approach is applied in this paper in order to model a more accurate life span of wind turbines by taking premature decommissioning and failures into account. A k value of 20 and a λ value of 0.0443 are applied in this paper. The decommissioned capacity is assumed to be installed again in the same year.

3.4. Installed capacity

The energy scenarios REMod-D by [2] and by Greenpeace [4] are selected to be investigated. While REMod-D proposes a 100 % renewable energy system in Germany in 2050, the Greenpeace scenario considers a 90% CO_2 reduction compared to 1990. The cumulative installed capacities of onshore and offshore wind turbines in 2050 from these scenarios are shown in table 4. The annual installed capacity is determined by linearly interpolating the cumulative installed capacity in 2016 and the values presented in table 4.

Table 4: Cumulative installed capacity of wind energy according to Greenpeace and REMod-D

	Greenpeace Onshore	*Greenpeace Offshore*	*REMod-D Onshore*	*REMod-D Offshore*
Cumulative installed capacity [GW]	95	52	200	85

3.5. Vector autoregressive analysis

The influence of the increase in demand on the steel price is investigated via a vector autoregressive analysis (VAR) analysis. Firstly, an Augmented-Dickey-Füller (ADF) test is conducted on every time series in order to determine the order of integration and the presence of a unit-root. The optimal lag length is determined by the method suggested by the authors in [54]. The results are crosschecked with a Kwiatkowski-Phillips-Schmidt-Shin (KPSS) test. In case of a unit root, the time series are transformed by calculating the log returns, in order to prevent problems for conventional inference procedures from ordinary least square regressions [55]. The maximum order of integration of the set of time series is set to 5. The maximum lag length of the variables in the VAR model is determined by the

Akaike and Bayesian information criteria as proposed by [56]. The following stable and invertible VAR-model is then set up.

$$Y_t = a_0 + \sum_{i=1}^{lag} b_i Y_{t-i} + +\varepsilon_t \tag{2}$$

For n number of variables, Y_t is a vector of length n, a_0 is a $[n \times 1]$ vector of constants, b_i are $[n \times n]$ coefficient matrices, i is the order of the VAR model and ε_t represents the matrix of residuals. In this paper, we have selected 8 variables as listed in table 7 to be included in the VAR model. Despite the availability of several steel-specific data such as import and export of iron ore, pig iron and scrap, they were discarded, with the exception of export of iron ore, upon conducting a preliminary Wald test, where no significant influence on the steel price could be identified. Besides microeconomic factors, we also included macroeconomic factors as proposed by [57] to complement the results and to control for macroeconomic influence. Since the oil price shocks have an impact on the steel price, as shown by [33] and [58], the West Texas Intermediate (WTI) oil price is also included as an endogenous factor in our model.

3.6. Impulse response function

In order to investigate the impacts of growing demand in the future on the steel price, the Monte Carlo method is employed to calculate the impulse response functions (IRF) analysis as mentioned in [59,60]. IRF is a system’s response to an impulse which can be defined as a function of time, given that the model is sufficiently linear and time-invariant [61]. A standard IRF procedure is to induce a shock to a single variable at a particular moment and to observe the evolution of the variables over time. In this paper however, multiple shocks are induced to the demand to represent the annual increase in steel demand due to the deployment of the wind turbines. A total of 1000 simulation runs for a period of 17 years until 2030 in the future is modelled.

4. Scenario definition

In order to describe and consider the uncertainties and possible developments of the wind energy sector in Germany, two different scenarios, conservative and upscaling, are defined. The fundamentals of these scenarios are similar to those proposed in [16]. The implementation of wind farms does not follow the same legal restrictions onshore and offshore; both markets are considered separately. The upscaling scenario is applied for both on- and offshore while the conservative scenario is only defined for onshore turbines.

Conservative - In the conservative scenario, the trend towards larger rotor diameters is assumed to be restrained by several factors: such as legally binding height limitations as well as infrastructural restrictions. In terms of infrastructure, greater transportation problems will occur for very large turbines due to the limitations of the road sizes in Germany. Due to that, electrically excited generator types will continue to have a higher market share in the future as there is no need for a technology overhaul. PM generators are assumed to eventually phase out completely by 2020. The conservative scenario is not assumed to be applicable to offshore since regulatory restrictions such as height restrictions and urban space competition are not present.

Upscaling - In the upscaling scenario, assuming that the technical challenges such as logistics and all of the aforementioned problems are resolved, the size of onshore wind turbines are expected to grow as explored and proposed by [15,62,63]. With bigger turbines, the market share is expected to shift towards PM generators. As for induction generators, a complete phase out seems unlikely to occur due to the maturity of the technology. Remaining potential near the shore will be utilized with DFIG but as deep water horizons are utilized, PM generators will be predominantly deployed. The complete market share of each generator types as well as the development of installed capacity and rotor diameter is shown in Appendix B: Table B3-B7. In all scenarios, production losses are taken into account by correcting the steel demand according to factor of 1.05, based on [64,65].

5. Data

In order to calculate the material composition, several LCA studies, as listed in table 5, from manufacturers and published studies are used as the basis to obtain data. In addition, data of turbine models, for which the masses of the rotor and the nacelle are available in manufacturer' sheets, is collected and applied for the upscaling of masses. These are listed in table 6.

Table 5: Overview of life cycle analysis of wind turbines analyzed in this paper

Manufacturer	*Rated Power [MW]*	*Rotor Diameter [m]*	*Drive Train System*	*Type of Tower*	*Source*
Enercon	2.3	82	EESG-DD	Concrete	[66]
Gamesa	2.0	90; 114	DFIG	Steel	[67]
Vestas	1.65; 2.0; 2.6; 3.0	82; 90; 100; 112	SCIG; PMSG-HS; DFIG	Steel	[68]

Table 6: Overview of data sample of wind turbine models applied for upscaling

Manufacturer	*Rated Power [MW]*	*Rotor Diameter [m]*	*Drive Train System*	*Source*
Adwen	5.0	135	PMSG-MS	[69,70]
Bonus Energy	1.3	62	SCIG	[71]
Enercon	0.9; 2.0; 3.05;7.58	44; 70; 80; 101;126	EESG-DD	[72,66,73]
Gamesa	2.0	80; 90; 114	DFIG	[67,74]
GE Energy	1.7; 4.1	100; 112.5	DFIG; PMSG-DD	[75,76]
NEG Micon	1.5; 2.0	64; 72	SCIG	[71]
Nordex	1.3; 1.5; 2.5; 3.0	62; 70; 100; 116	SCIG; DFIG	[71,77]
Vestas	0.85; 1.75; 2.0; 2.6; 3.0; 3.3	52; 66; 90; 100; 112	SCIG; PMSG-HS; DFIG	[68]
Vestas MHI	8.0	164	PMSG-MS	[78]
Senvion	2.05; 3.2; 3.4; 3.6; 6.2;	82; 92; 100; 114;	DFIG	[79]

		104; 122; 126; 152		
Siemens	2.3; 3.2; 4.0; 6.0	93; 101; 108; 120; 113; 120; 130; 154	SCIG; PMSG-DD	[80]
WinWind	1.0	56	PMSG-MS	[71]

An overview of factors applied in the VAR model is presented in table 7. The microeconomic variables are available from 1968 onwards and are only available in annual frequency. Therefore, the annual average values of the macroeconomic values are calculated for the VAR analysis.

Table 7: Overview of fundamental factors included in this paper

Factors	*Description*	*Source*
Price	European steel price	Federal Institute for Geosciences and Natural Resources (BGR)
Apparent consumption	Apparent consumption in Germany	World Steel Association
Production	Steel production in Germany	World Steel Association
Export of iron ore	Export of iron ore from Germany	World Steel Association
GDP	Seasonally adjusted gross domestic product of Germany	German National Bank
CPI	Seasonally adjusted consumer price index of Germany	German National Bank
Yields	Yields on debt securities outstanding of Germany	German National Bank
Oil Price	Oil price: West Texas Intermediate (WTI)	Federal Reserve Bank of St. Louis

Table 8: Descriptive statistics of log returns of the fundamental factors

Factors	*Data points*	*mean*	*median*	*SD*	*min lag*	*ADF statistic*	*t-stat*
Price	43	0.04012	0.04505	0.17329	1	-4.4326	0.0546
Apparent consumption	43	0.00376	0.00722	0.12721	2	-5.4871	-2.9506
Production	43	0.00134	0.00042	0.10468	2	-6.4994	-3.6277
Export of iron ore	43	0.03778	0.00000	0.83781	1	-5.2643	-.13152
GDP	43	0.01942	0.01933	0.02025	1	-3.1538	3.6143
CPI	43	0.02687	0.02176	0.01763	2	-3.4640	4.1449
Yields	43	-0.04290	-0.03049	0.16361	1	-3.3210	1.1275
Oil Price	43	0.07892	0.07147	0.26589	3	-2.9429	0.7048

6. Results and discussion

Figure 1 shows the annual total steel demand due to the deployment of wind turbines in Germany until 2050 according to the REMod-D and Greenpeace energy scenarios. The steel demand increases gradually in all scenarios, whereby the demand in 2050 alone varies between 2,000 (in the Greenpeace conservative scenario) and 5,900 kt (in the REMod-D upscaling scenario). In comparison, the total production as well as apparent consumption of steel in Germany in 2015 was around 42,000 kt, which means that a supply bottleneck is unlikely to occur. From 2012 to 2050, the cumulative steel demand lies between 50,000 and 58,000 kt for the Greenpeace energy scenario, and between 94,000 and 116,000 kt tons for the REMod-D scenario respectively. In [16], the authors estimated - for a cumulative installed capacity of 249 GW - the cumulative steel demand until 2050 to be 57,300 kt. Despite comparable cumulative installed capacities with the REMod-D scenario, this estimate is lesser than the demand determined in this paper due to the fact that the additional steel demand through wind turbine repowering was not considered in their study.

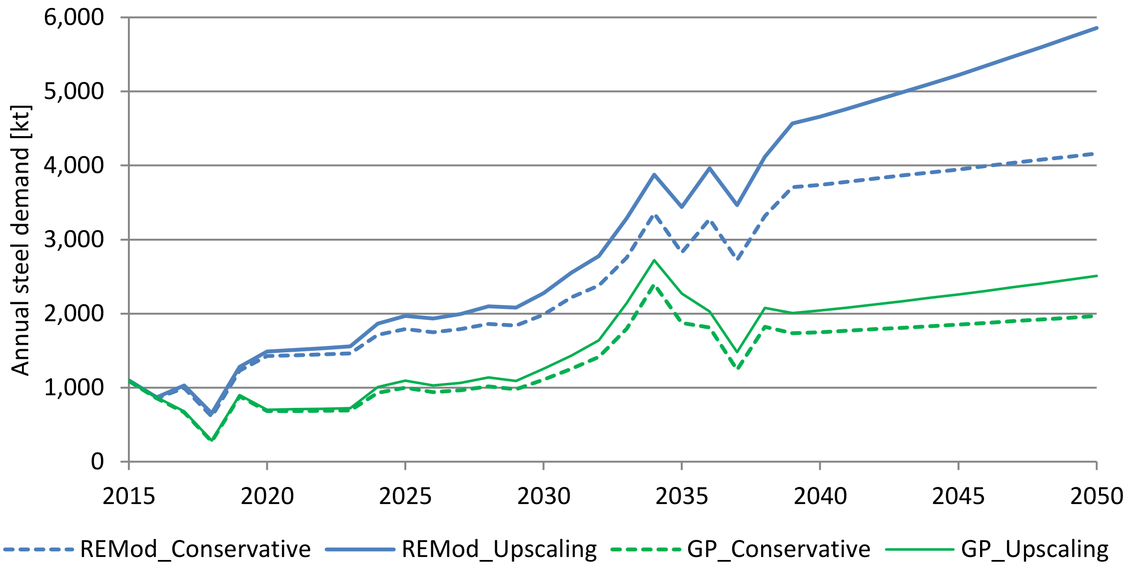

Figure 1: Total steel demand in the wind energy sector in Germany

According to a study by the Federation of German Industries (BDI) in 2012, the cumulative steel demand until 2020 was then estimated to be 4.5 million tons [7]. In this paper, the range of the demand in the same period is calculated to be between 5.6 and 7.5 million tons. This suggests that the prediction from BDI was most probably underestimated as the portfolio changes of the manufacturer and the actual planned wind farms in the North and Baltic seas were not considered. Further comparisons with the existing literature tend to be limited, as most papers take a steel recycling rate into account. No convincing data was found indicating the amount of scrap metal from wind turbines that is directly being recycled to produce new turbines i.e. the steel recycling is currently not a closed loop in the wind energy industry. The results presented are under the assumption that the material composition of a wind turbine will not undergo significant structural changes in the next years.

The results of the ADF tests show that a unit root is present in all time series. Therefore we calculated the log returns of the time series and conducted the ADF test again, to find that the unit roots were successfully removed. A crosscheck with KPSS test further validated the results. The maximum lag length of the VAR model is calculated to be 1 according to both Akaike and Bayesian information criteria. The coefficient estimates of price and demand, denoted by *b* in equation 2, by the VAR model is shown in table 9.

Table 9: Coefficient estimates of the VAR model for price and demand. The complete coefficient estimates are listed in Appendix C

	Price	*Demand*	*Production*	*GDP*	*CPI*	*Yields*	*Export Ore*	*Oil Price*
Price	0.0474	0.2745	0.3830	-3.7859	-4.9888	-0.1058	-0.1281	0.1073
Std. Error	0.190	0.422	0.503	2.415	2.081	0.175	0.212	0.119
t-Statistic	0.249	0.650	0.761	-1.567	-2.397	-0.605	-0.604	0.899
Demand	-0.1627	-0.0420	-0.1392	-0.7986	-3.4104	-0.1120	0.1046	0.0142
Std. Error	0.130	0.288	0.344	1.649	1.421	0.119	0.145	0.082
t-Statistic	-1.251	-0.146	-0.405	-0.484	-2.400	-0.938	0.722	0.174

As observed in table 9, the estimated demand coefficient with respect to price of 0.2745 represents the price elasticity of steel demand. It means that a 10 percent increase in demand, holding constant the effects of all other factors, results in a 2.745 % increase in the steel price. Taking the interactions between all factors into consideration, the future prices until 2030 is then forecasted. In order to investigate the effects of the increasing demand due to the wind turbines on the price, two cases are analyzed. Firstly, the natural growth of the steel price is modelled as no demand shock was induced in the IRF model. In the next case, the additional annual steel demand based on the REMod-D upscaling scenario is modeled as annual shocks to the steel demand. Both results are shown in figure 2.

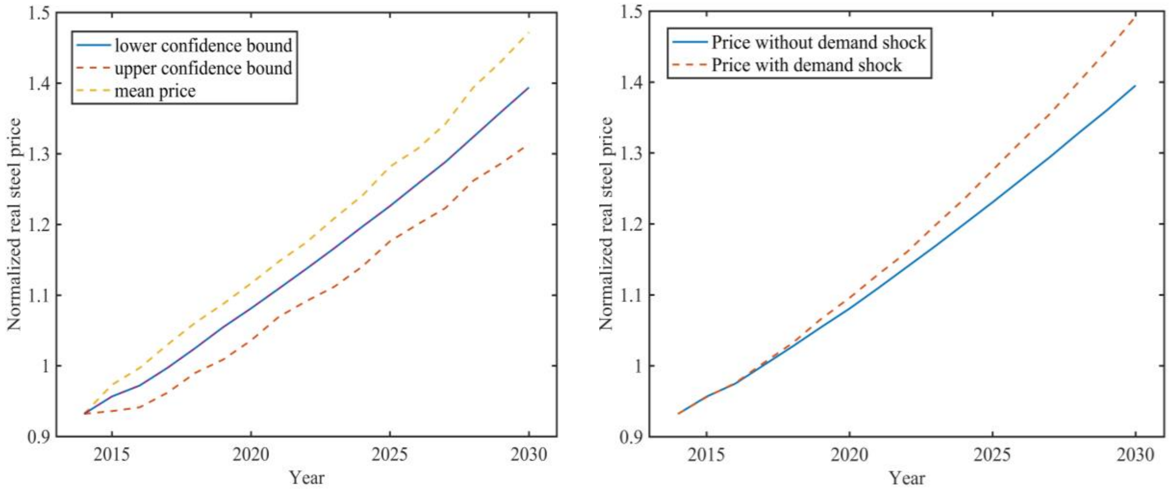

Figure 2: Normalized steel price with 95 % confidence intervals without demand shocks (left) and effects of a demand shock according to the REMod-D upscaling scenario on the steel price (right)

Between 1971 and 2013, the real steel price has increased with a compound annual growth rate (CAGR) of 1.3 % p.a. This is especially due to the strong increase in steel price in the last 30 years at 2.5 % p.a. In our results, the steel price in the first case has a growth of 2.4 % p.a. until 2030. In the second case, the growth rate of steel price increases minimally by 0.4 %. On one hand, this is owed to the fact that the steel production in Germany is not affected by the demand shock. The steel production in Germany has experienced an average increment of 0.4 % p.a. between 2003 and 2016. In our model, we found that the CAGR of steel production will remain at 0.1 % until 2030 in both cases. Even the CAGR of iron ore export remains unchanged despite the demand shocks. On the other hand, the demand increases at a greater rate due to the increasing wind turbine deployment. Based on our results, the CAGR of the steel demand in Germany in the second case is calculated to be 2.9 % p.a. However, the increment in the steel price due to the demand shocks is considerably lower than that observed in the steel demand. The total steel demand in Germany will increase at much greater rate than the additional demand due to wind turbine deployment. The induced demand shocks are absorbed by the model, thus limiting the impact on the price. It can therefore be concluded that the increase in steel demand due to wind energy deployment in Germany only have a minimal impact on the European steel price.

7. Conclusion

In this paper, we presented an approach to combine raw material demand analysis of an energy technology and econometric methods in order to analyze the effects of an increasing share of renewable energies on the raw material price. This approach is applied exemplarily to determine the economic impacts of the wind energy sector on the steel market. The steel demand is determined separately for the rotor, nacelle, tower and foundation of a wind turbine. Two scenarios were defined for the onshore generator market share to take any possible structural change in the market situation and manufacturer portfolios in the future into account. The economic impacts were determined via a vector autoregressive model (VAR) and impulse response function (IRF).

The results show that the steel demand due to the deployment of wind turbines increases gradually until 2050. Depending on the market development, the annual steel demand in 2050 could vary between 2,000 and 5,900 kt. With respect to the current steel production level in Germany, a bottleneck in the steel supply is therefore not foreseeable. Results from the IRF show that additional demand from the wind energy sector according to REMod-D upscaling scenario is minimal compared to the overall increase of total steel demand in Germany. The impacts of other scenarios are therefore expected to be even smaller due to their respective lesser steel requirement. The real steel price is expected to rise 2.4 % per year on average, with the additional steel demand from the wind sector contributing to a further 0.4 % increment on average. The annual growth of production and export of steel remains on average unchanged.

Overall, we showed that the approaches presented in this paper can be applied to combine raw material demand analysis and econometrics to determine economic impacts of growing material demand from any energy technology. Further works are required to determine the total material demand within an energy system to analyze its economic impacts as a whole on the material prices and other fundamental economic factors. In addition, the proposed VAR model has to be further enhanced by testing and expanding it to accommodate more relevant fundamental variables and to model the economic impacts more precisely.

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Appendix A: Constant and Scaling factor for the turbine Upscaling

$$M \propto a * D^{b} \tag{A1}$$

M: Mass of each component
a: Constant factor
D: Rotor diameter
b: Scaling factor

The constant and scaling factors of each component are determined by curve fitting historical data of wind turbines, as listed in table 6. These factors are used to model a curve that describes the weight of a component with respect to the rotor diameter of wind turbines in the future.

Table A1: Constant and scaling factors for all components and scenarios

	Rotor mass		*Nacelle mass*								*Tower mass*	
			DFIG		*EESG-DD*	*PMSG-MS/HS*		*SCIG*		*PMSG-DD*	*Steel type*	*Concrete type*
Scenario	*Conservative*	*Upscaling*	*Conservative*	*Upscaling*		*Conservative*	*Upscaling*	*Conservative*	*Upscaling*			
Log (a)	-2.31	-3.34	-3.43	-3.34	-2.09	-2.27	-2.09	-1.24	-2.12	-2.09	-1.22	-0.57
b	2.03	2.56	2.69	2.56	2.07	2.13	2.07	1.60	2.07	2.07	3.22	3.22

Appendix B: Market shares of wind turbine components

Table B1: Market shares of steel and concrete towers

	Onshore			*Offshore*		
	2010	*2025*	*2050*	*2010*	*2025*	*2050*
steel towers [%]	90	80	60	100	90	80
concrete towers [%]	10	20	40	0	10	20

Table B2: Current and future market shares of offshore foundation types. The market shares from 2017-2019 is obtained from approved wind farms that are currently being built

	2015	*2016*	*2017*	*2018*	*2019*	*2025*	*2030*	*2035*	*2040*	*2050*
Monopile	56.0	100	79.1	0	78.1	56.9	66.7	30.0	20.0	10.0
Tripod	24.5	0	0	0	12.2	19.0	33.3	60.0	65.0	60.0
Jacket	19.5	0	20.9	100	9.6	24.2	0	5.0	5.0	10.0
TLB	0	0	0	0	0	0	0	5.0	10.0	20.0

Table B3: Historical and assumed future market shares of onshore generator types according to the conservative scenario

	2014	*2015*	*2016*	*2020*	*2030*	*2040*	*2050*
EESG-DD	43	37	43	38	37	36	35
SCIG FC	8	14	24	25	22	19	16
PMSG-HS	14	9	1	0	0	0	0
PMSG-DD	5	3	1	0	0	0	0
DFIG	29	38	31	37	40	43	46
PMSG-MS	0	0	0	0	1	2	3

Table B4: Historical and assumed future market shares of generator types onshore according to the upscaling scenario

	2014	*2015*	*2016*	*2020*	*2030*	*2040*	*2050*
EESG-DD	43	37	43	28	8	2	1
SCIG FC	8	14	24	15	12	9	9
PMSG-HS	14	9	1	7	19	28	28
PMSG-DD	5	3	1	10	23	32	33
DFIG	29	38	31	40	32	24	24
PMSG-MS	0	0	0	0	6	5	5

Table B5: Historical and assumed future market shares of generator types offshore according to the upscaling scenario

	2014	*2015*	*2016*	*2020*	*2030*	*2040*	*2050*
EESG-DD	0	0	0	0	0	0	0
SCIG FC	87	64	22	0	0	0	0
PMSG-HS	0	0	0	0	0	0	0
PMSG-DD	0	0	78	54	50	47	46
DFIG	3	12	0	17	9	4	2
PMSG-MS	10	24	0	28	41	49	52

Table B6: Assumed development of the average nominal power of wind turbines

	2014	*2015*	*2016*	*2020*	*2030*	*2040*	*2050*
Onshore conservative	2.7	2.7	2.8	3.1	3.7	4.1	4.2
Onshore upscaling	2.7	2.7	2.8	3.3	4.4	5.5	6.7
Offshore	3.7	4.1	5.2	7.3	11.6	15.8	20.0

Table B7: Assumed development of the average rotor diameter of wind turbines

	2014	*2015*	*2016*	*2020*	*2030*	*2040*	*2050*
Onshore conservative	99	105	109	110	127	138	141
Onshore upscaling	99	105	109	116	146	176	207
Offshore	120	120	145	160	190	220	250

Appendix C: Coefficient estimators of the VAR model.

	Price	*Demand*	*Production*	*GDP*	*CPI*	*Yields*	*Export Ore*	*Oil Price*
Price	0.0474	0.2745	0.3830	-3.7859	-4.9888	-0.1058	-0.1281	0.1073
Demand	-0.1627	-0.0420	-0.1392	-0.7986	-3.4104	-0.1120	0.1046	0.0142
Production	-0.1872	-0.1197	-0.1693	0.8607	-2.7690	-0.0670	0.1131	-0.0447
GDP	-0.0220	0.0370	-0.0741	0.2648	-0.6199	-0.0145	0.0158	0.0051
CPI	-0.0060	-0.0113	0.0256	0.0856	0.6679	0.0112	-0.0061	0.0041
Yields	0.0619	-0.3934	0.6150	0.6438	-3.8190	0.0985	-0.1365	0.0282
Export Ore	-0.4414	0.1970	0.3253	-3.7471	-2.5530	-0.1217	0.3667	0.0325
Oil Price	0.1047	-0.4160	0.0851	1.4167	0.5172	0.1969	0.3609	-0.1506