The Future Is Colorful—An Analysis of the CO₂ Bow Wave and Why Green Hydrogen Cannot Do It Alone

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Abstract: In both the private and public sectors, green hydrogen is treated as a promising alternative to fossil energy commodities. However, building up production capacities involves significant carbon production, especially when considering secondary infrastructure, e.g., renewable power sources. The amount of required capacity as well as the carbon production involved is calculated in this article. Using Germany as an example we show that the switch to purely green hydrogen involves significant bow waves in terms of carbon production as well as financial and resource demand. An economic model for an optimal decision is derived and—based on empirical estimates—calibrated. It shows that, even if green hydrogen is a competitive technology in the future, using alternatives like turquoise hydrogen or carbon capture and storage is necessary to significantly reduce or even avoid the mentioned bow waves.

Keywords: hydrogen; CO₂; wind power; electrolyzer; bow wave

1. Introduction

The recent public debate about green energy technology is fairly binary and often with a predetermined result: fossil technologies such as gas or coal fired power plants or fossil fuels themselves (oil, gas, coal) are considered to be dinosaurs that have to disappear very quickly. Further explorations are supposed to be canceled, as Denmark recently decided to do [1]. In the future, energy generation should be renewable. As a potential storage material, hydrogen (H₂) is considered to be promising and considerable research has been invested into this matter [2–5]. Scientists and industry discriminate between different colors of hydrogen depending on the method of production: Green hydrogen, for example, implies that production is (almost) CO₂-neutral using e.g., bio gas or renewable energies such as wind power; whereas gray hydrogen is produced using fossil fuels such as oil or gas. Turquoise hydrogen implies using methane pyrolysis fueled by renewable energy sources, i.e., it is also considered to be CO₂-neutral. Eventually, blue hydrogen denotes the combination of steam reforming with a carbon capture and storage (CCS) procedure. This version is often regarded as bridge technology on the way towards a carbon-neutral economy [6], whereby it is often assumed in public and demanded by some non-governmental organizations that the switch from fossil to renewable energy production can be done within a very short period of time of, say, a couple of years. This article intends to test this hypothesis using Germany as an example, whereby we focus on green hydrogen. We therefore consider the involved numbers, e.g., the commodity demand for building enough wind mills or the corresponding needed investment demand. Our calculations show that even if technologies are (almost) ready for installation on a scalable and economically sustainable price level, which is hardly realistic even in a very optimistic setup, we face a significant CO₂ bow wave (see Section 3). To switch from...
gray, blue, or turquoise to 100% green hydrogen, a substantial investment into green power generation—including a new distribution infrastructure (H₂ pipeline and electricity grid)—is necessary. This includes a substantial amount of new wind turbines, solar power panels, power cables, hydrogen tankers, etc., which all have to be produced first. Even if we assume some effects from previously installed green devices, most of the production will be done with conventional technologies, whereby—in Section 3—we give a rough estimation about the required demand for Germany. All of these undertakings will produce CO₂. This greenhouse gas is a stock pollutant, which means we will have to pay a heavy price for these construction efforts as it turns out not to be simply an investment into fewer emissions later. Such assumptions are a wrong understanding of intertemporal dynamics. A key element of a successful green deal will be to reduce emissions in heavy industries as quickly and cheaply as possible to provide a sustainable path towards a true green economy. According to our calculations it is reasonable to apply blue or turquoise hydrogen as an immediate carbon-saving technology that helps lower the impact of all efforts to set up a green hydrogen infrastructure. Note that doubts on this hypothesis are not new [6] and there is a wide discussion going on in public and the science community.

Besides the mentioned CO₂ effects, there is also the issue of keeping public spending down. Considering the current developments on the commodity markets it is a reasonable assumption that, within the next 10 years, the price of each megaton (Mt) of CO₂ not produced due to green hydrogen will be multiple of a Mt of CO₂ avoided using a ‘multi-color’ hydrogen approach. Both wind turbines and solar panels are high-tech products involving rare earths and common materials like concrete or steel. Already now economists discuss the issue of resource/commodity availability as well as prices and therefore implied inflation and stability of the macro economy [7]. Currently, we see a massive increase of the prices for critical materials such as platinum, rhodium, copper, lithium, cobalt, or iron. Since also an additional build-up of production sites have to be done this will likely hit the market for steel, concrete, and aluminum. To avoid such a price squeeze and later on an also disastrous sudden price drop in the aftermath of the demand peak, a social input management is necessary, which especially includes existing technologies and production sites, e.g., (as mentioned above) blue and turquoise hydrogen. Besides, this resource run may cause significant CO₂ emissions in mining and transportation, although the quantity is hard to estimate. To conclude: according to estimates (e.g., by Greenpeace Energy [8]), green technologies will be competitive from around 2040–2050 onwards. In order to avoid the above mentioned financial and carbon bow wave bridge technologies such as turquoise hydrogen or blue hydrogen plus CCS are required.

The purpose of this article is two-fold: first, in order to verify the above statements and assumptions, different kinds of bow waves like the carbon or the financial bow wave are quantified. Most numbers are already available in different sources. However, aggregating and connecting them provides a fundament for the ongoing public debate and indicates the direction of further research. Especially bundling the financial and carbon point of view with the corresponding resources demand provides relevant additional information since the latter is expected to have a significant economic impact. Second, we set up a novel theoretical economic model for the optimal choice of hydrogen color. Here we introduce—besides the internalization of the resource costs—also turquoise hydrogen as a technology option. This allows to test the implication of various changes to the system, e.g., by introducing hydrogen subsidies.

The article is thereby structured as follows: In Section 2, relevant information about the involved technologies is given. Section 3 contains an empirical quantification of different kinds of carbon bow waves. Eventually, numbers from Section 3 are used in a theoretical model in Section 4. Section 5 evaluates the results, and Section 6 concludes the article.
2. Technologies for Hydrogen Production

For a better understanding of Section 3, we discuss the colors of hydrogen more in detail (Section 2.1), and briefly talk about features of electrolysis like technology readiness and efficiency (Section 2.2). Wind power is introduced in Section 2.3. Section 2.4 comments on the costs of different hydrogen colors. Eventually, in Section 2.5, the timing of investment as one key element of the bow waves is discussed.

2.1. Different Colors of Hydrogen

Both literature and practice use a color scheme to categorize hydrogen production according to the applied procedure [6,9]. Green hydrogen refers to the application of electrolysis (see Section 2.2) which only generates hydrogen and oxygen—hence no emissions at all. For fueling the electrolysis only renewable energy like wind, water, or solar power is used. The opposite is gray hydrogen, which denotes the application of steam methane reforming [10] or auto thermal reforming (ATR) [11,12] to produce hydrogen with CO\textsubscript{2} as by-product. Here, the CO\textsubscript{2} is not captured but released to the atmosphere. For more technical details, please refer to [10–12]. Blue hydrogen, again, is basically gray hydrogen but where CO\textsubscript{2} is captured and stored. There are different concepts to implement CCS [13,14]. Especially the Norwegian energy company Equinor has been very active lately: together with Total Energy and Shell, two other major European energy companies, Equinor launched the so-called Northern Lights project to store CO\textsubscript{2} in the ground below the Northern Sea [15]. Eventually, there is turquoise hydrogen, which denotes H\textsubscript{2} production via methane pyrolysis. It is supposed that the energy demand here is satisfied by renewable sources, so the result of the procedure is, besides hydrogen, only carbon black [16,17]. As now turquoise hydrogen looks like an equal competitor to green hydrogen we have a closer look at the CO\textsubscript{2} balance. Actually, as described by [16] for example, there are some CO\textsubscript{2} emission linked to transport and production. From a footprint and a stand-alone full cycle point of view this is correct, but considering the bow wave and marginal point of view at least parts of this emissions if not almost all may not be relevant due to three reasons: First, emission linked to grid use would still be there, and reducing demand would only increase the footprint of the remaining gas usage since gas combustion has a non-linear relationship between output and emission. Second, it is very unlikely that the gas grid will stay active at the recent emission levels seeing all operating companies under pressure by environmental social governance expectations. Third, there is some research about using solid carbon in industry—e.g., for tire production or making lighter concrete [18–20]—which would have positive effects on the CO\textsubscript{2} balance. Further research is needed to calculate a reliable net footprint; however, in this paper we neglect the emission, but will add a certain sensitivity analysis in our summary. Besides, our model in Section 4 can theoretically include a possible CO\textsubscript{2} footprint. In Germany, there are already a couple of companies promoting pyrolysis with a technology readiness level (TRL) of 6–8 based on different kinds of plasma arcs [21] like the German company Graforce [22], the British company HiiROC, or the Canada-based company Pyrogenesis. Here, using renewable energy, natural gas is decomposed into H\textsubscript{2} and carbon black without any or only insignificant CO\textsubscript{2} production on lifecycle basis. On TRL 4–6 are pyrolysis technologies like molten metal reactors [23] or moving bed reactors [24]. These reactors are considered to be more efficient. The advantage is that less green energy is needed. According to Graforce [22], only 10 kWh of energy is needed to produce 1 kg of hydrogen, while green hydrogen needs (assuming an optimistic electrolyzer efficiency of about 80%, see Section 2.2) around 41 kWh. Thus, about 4 times less green energy build-up is necessary, which will be an important issue in our analysis below.

Lately, yellow hydrogen has been added to the color scheme, which is only mentioned for the sake of completeness—especially because the definition is ambiguous: some authors mean hydrogen produced using solar power (and electrolysis) and some refer to hydrogen production using nuclear power [9].
2.2. Electrolyzer Technologies

An electrolyzer splits up water into hydrogen and oxygen. There are various potential technologies, namely the alkaline water electrolysis, the proton exchange membrane (PEM) electrolysis, the anion exchange membrane (AEM) electrolysis and the solid oxide electrolysis, which requires comparably high temperature levels [25–28]. Mougin [29] estimates that the electric efficiency of the high-temperature electrolysis is about 89% compared to the 58% of the alkaline water electrolysis and 63% of the PEM electrolysis. A study conducted by the International Renewable Energy Agency (IRENA) [30] estimates slightly higher efficiency values, i.e., 50–83% for the PEM and between 50% and 78% for the alkaline water electrolysis [28]. The PEM procedure uses platinum and iridium for the electrodes and is already commercially available—however, not for an application on an industrial level yet. On the contrary, the alkaline electrolysis is already well established in industry and only requires fairly cheap materials for the electrodes, namely nickel and iron. Both procedures have a similar specific energy demand. Currently, electrolyzers are designed mainly for fresh water; however, lately, there are efforts to adapt these systems to salt water conditions while keeping efficiency losses at bay [31–33]. Alternatively, one can first generate distilled water from seawater which is then fed to the electrolyzer. Desalination is expensive and energy-intensive though, and there is ongoing research into how to reduce the costs of this step. Energy demand for a fresh water-based alkaline electrolysis is between 4.2 and 5.8 kWh/m$^3$ of H$_2$ [26]. In the case of salt water, the demand is tendentially higher.

2.3. Wind Power Generation

Here, we do not describe the physical model of wind power production in detail; for more information, please refer to [34] or [35]. However, a few facts should be mentioned. First and foremost: There is a difference between on—and offshore wind production—at least in Europe. Wind is much more steady at sea, which is why offshore turbines and rotor blades are normally larger and more powerful than onshore facilities [35]. Note that, for reasons of simplicity, we only consider wind turbines as green energy source in this article, which is a rather positive view on renewable energies since the average CO$_2$ invest for solar panel farms is higher [36–38]. Besides, turbine size has been increasing over the past few years. Recently, a new class of Giga wind turbines like General Electric’s Haliade X with 10 MW power or more has been designed. Forbes, a magazine, quotes a Bernstein research study that sees the carbon output of the Haliade-X turbine at a level of only 6 g/kWh [39]. Other, more scientific studies, estimate that carbon emissions of wind turbines range between 10 and 20 g/kWh [40,41], although the results of Reimers et al. [40] might be outdated by now. New types are likely to produce less CO$_2$, but reliable numbers are hard to obtain. Note that this numbers typically consider all emissions generated by installing the wind power turbines including transport and connection efforts as well as materials. Since it would be too optimistic to assume that all new turbines will be as efficient as the Haliade type we introduce—based on [42]—two abstract model wind turbines, which are described in detail in Appendix A: Type 1 represent a modern onshore type like the Nordex N149 while Type 2 is based on an average state of the art offshore model like the Vestas V164. Eventually, it is likely that technological progress and larger turbines will further reduce the amount of involved CO$_2$ production and minerals demand, but this will only soften the below described bow waves. We will address this fact in our final analysis, but since exact data for the new models are not published yet the effects would have been guesswork anyway.

2.4. Cost Structure of Hydrogen

As most authors do, we focus solely on the generation costs, not on the costs for setting up the infrastructure. Different authors expect that between 2030–2040 we will reach the break-even point between all technologies [6,21]. This is a straightforward assumption, since hydrogen itself is a homogenous good and consequently we face a
Bertrand competition. Expensive generation can only exist via subsidies or if generation is a bottleneck. If a competitive and fairly liquid hydrogen market arises, we will see an equilibrium on the medium term. Based on the quoted sources we derive the numbers displayed in Table 1 (using a 1:1 exchange rate for USD and EUR).

Table 1. Cost structure of hydrogen according to color.

| EUR/kg | 2022 | 2030 |
|--------|------|------|
| Scenario | Min  | Max  | Min  | Max  |
| Green   | 2.5  | 4.5  | 1.25 | 2.5  |
| Blue    | 1.5  | 2.8  | 1.5  | 2.8  |
| Turquoise | 2.55 | 5    | 1.275 | 2.5 |

In case of renewable generation this is a very optimistic assumption, even supportive sources like Greenpeace Energy [8] expect (in more cautious scenarios) that green hydrogen may have a cost disadvantage. However, in this study, we assume equal cost structures in generation (see Section 4). This seems to be likely, nevertheless it is a very friendly assumption regarding green generation.

2.5. Timing of Investments

One important issue when tackling the problem of carbon-production is the intertemporal aspect of the investment, as von Döllen and Requarte [43] argued. The advantage especially of turquoise hydrogen is that for methane-based hydrogen most of the necessary infrastructure is available. While for blue hydrogen an investment into CO\textsubscript{2} transport and CCS infrastructure is needed, turquoise hydrogen—initially based on the close-to-market plasma bow technology—can be quickly produced anywhere where gas and power grids exist. Only the necessary build-up of green generation has to be considered, but since the demand, as stated above, is only one quarter, this relaxes the investment needs a bit. It would yield a certain degree of freedom by providing quick CO\textsubscript{2}-free hydrogen for steel, concrete, etc., commodities that are much needed for wind power (as described in the next section).

3. Empirical Evidence for Upcoming Bow Waves

We quantify the effect of an investment into renewable energy facilities in three dimensions: the amount of carbon produced (Section 3.1), the financial effect (Section 3.2), and the effect on resources (Section 3.3).

3.1. Carbon Bow Wave

According to the German hydrogen strategy [44] 90 TWh to 110 TWh hydrogen is needed until 2030. Thereby, at least 14 TWh shall be green. For this purpose, a massive build-up is necessary to reduce the share of conventional hydrogen, which is likely to happen from 2025 onwards. Besides, significant additional emissions will be caused by the federal efforts to increase the number of electric vehicles on German roads. We estimate the total CO\textsubscript{2} bow wave to be between 14–17 Mt until 2030 (i.e., 1.6–1.9 Mt per year) only for the German demand. Note that not every emission will be within Germany, but to be CO\textsubscript{2} neutral we also have to avoid emissions somewhere else. The above numbers are calculated as follows: Considering an average turbine power of 4 to 8 MW (Type 1 or Type 2 from Section 2.3 and the Appendix A), a CO\textsubscript{2} emission per turbine between 8 and 10 g/kWh, as well as an electrolyzer efficiency of 70% we need about 650 (Type 2) to 1400 (Type 1) (Section 2.2, Section 2.3, Section 2.4 and Appendix A) turbines producing the energy for 14 TWh of green hydrogen. i.e., in sum 3.3 to 4 Mt of CO\textsubscript{2} until 2030. If you consider the demand for the energy transition done straight forward by the publicly discussed and politically demanded fossil-to-green-move coined ‘Energiewende’ in Germany (in English, ‘energy change’), we talk about 2200 (Type 2) to 4700 (Type 1) wind turbines inducing 10.7
to 13 Mt of CO$_2$ (production and operation). This assumption includes 10 million electric vehicles based on the energy consumption of the Volkswagen ID.3 [45] or a comparable car as well as the 65% green target for the existing energy demand. If we now assume that also the missing 76 TWh of the mentioned H$_2$ minimum target are green, additional approx. 3570–7760 wind turbines are required, which means additional 18–22 Mt CO$_2$ or 2–2.4 Mt CO$_2$/year. According to the Federal Environmental Agency, Germany emitted 740 Mt in 2020 and targets 560 t in 2030 [46]. Therefore, considering the above described all-green scenario, we talk about an increase of 5–10%/year for the next 9 years. Besides, we have to consider battery storages and batteries for electric vehicles. If we assume an average demand of 1 million vehicles per year and assume that one car battery causes (at least) 8 t of emissions [47–49], we have about additional 8 Mt CO$_2$/year, most of it emitted before significant additional green power will be available.

Last but not least, there is a massive investment in infrastructure on the horizon [50]. Green power has to be stored and distributed, and there is substantial room for doubt that a switch from natural gas to hydrogen is realistic without building additional hydrogen pipelines: First, hydrogen has a different chemical and physical behavior, and there is ongoing scientific discussion and doubts about if and to what extent the current natural gas pipeline infrastructure can be used for hydrogen transporting purposes [51–53]. Second, as the aforementioned sources state, we can add maximum about 10% (some authors say up to 17%) of hydrogen to the current grid in order to replace natural gas. However, if we want to use (hydrogen-fueled) power cells on a big scale, i.e., say also for heating, we will end up in a binary decision (hydrogen or gas) and it seems unrealistic to switch a full city immediately from one technology to the other. Thus, at least for a certain period of time, we need two grids at least for the transport from the production site to the end user. At this point, we have not even considered yet that, in order to produce such additional amounts of solar panels, wind turbines, batteries and other devices, a massive investment into additional production capacity is needed, which significantly increases the consumption of concrete, steel, and aluminum [54]. According to Shang [55], 1.5 MW installed wind capacity needs 400 m$^3$ concrete with a carbon footprint of 0.54 t CO$_2$/ton, i.e., 225 kg/m$^3$ [56,57]. Our calculations yield about 900–1500 tons of CO$_2$ resulting from concrete production. Given these numbers and the concrete demand per turbine (For details see Section 5) we estimate that concrete is responsible for about 20% (offshore) to 40% (onshore) of the CO$_2$ emissions linked to a turbine installation. So, from an intertemporal point of view, focusing on industry first has the potential to soften the bow wave, because we reduce in this way the carbon footprint. If we also consider steel, where we have 1.7 t CO$_2$/t steel [58], 50% to 70% of the emissions of a future wind turbine installation could be avoided in the best case. Even if we consider not pure green hydrogen production but only the 80–90% reduction by using blue hydrogen, CO$_2$ production can be reduced by 40% to 55%, which corresponds with other sources [6].

Note that this would also be a valid strategy for a pure green hydrogen pathway, but due to the lesser efficiency (Section 2) of the currently available technology and the higher green power demand the softening effect would be significantly smaller. Eventually, we need to consider the emissions generated when producing and installing electrolyzers and other required equipment. Since we guess that this will be comparable with the installation and production of CO$_2$ capturing devices, steam reformers, and turquoise production units, we ignore this issue here as ‘fixed’ price for the transitions for which we see no easy way to minimize.

3.2. Financial Bow Wave

Our calculations are mainly based on Table 1 from Section 2.4. To install a certain number of TWh of green hydrogen, we need the installation of a corresponding amount of green energy. Assuming an electrolyzer efficiency of (rather friendly) 70%, we need 1.43 TWh of renewable energy which is in line with the assumptions of the German hydrogen strategy 2030 [44]. If we use the German hydrogen target as a baseline or base case (14 TWh), we talk about 20 TWh of required energy. To simplify the model and get an
easier idea of what it means we will assume (as specified above) that the power will be generated either by offshore (Type 2) or onshore (Type 1) wind turbines. One can extend the model to solar power, onshore wind, and water; however, one quickly sees that this may soften the problem but will not solve it.

As described in Section 2.3 we assume a runtime of 3500 to 3800 full load hours (flh) per year for Type 1 and Type 2 turbines, respectively. To estimate the costs involved we use data from literature [30,59,60]. First of all, we take a look of the onshore cost level (in our model Type 1 turbines). Blazquez. et al., from the Oxford Institut of Energy Studies [60] for example, estimates that for onshore turbines the best projects reach leverage costs of 50 Eur/MWh. Assuming 20 years and 3500 flh/year and assuming 31% to be investment costs [59] we arrive at total costs of 1.2 bn EUR per installed GW, which correspond with the numbers in the IRENA study 2021 [30]. In the Irena study 2021 [30] offshore wind (in our model Type 2 turbines) is seen at 3185 USD/kWh, which means about 2.7 bn Eur/GWh. For our modeled turbine types, we therefore see cost between 4–20 million EUR per turbine. This sums up to 26 to 60 bn EUR investment for the Germany base case (i.e., energy transition target plus e-mobility target plus 14 TWh green hydrogen) and 60 to 140 bn EUR for the all-green case.

To sum up our calculations until now: if we intend to produce all required energy using wind power, it would require investments until 2030 of at least 26 bn EUR—only for Germany and considering that we would use the cheaper onshore option which seems not very likely. Reaching the minimum target is already very ambitious and the all-green scenario would be a substantial investment, especially considering how the COVID pandemic has been already quite a burden on public finance.

Eventually, looking at the capital expenditure, one has to keep in mind that one MWh of green hydrogen will be at least 30 to 50 EUR/MWh more expensive compared to blue or turquoise hydrogen due [61]. Even if we relax that to 10 EUR/MWh assuming a quick progress in production efficiency we talk about 0.14 bn EUR of additional costs for the 14 TWh and 0.9 bn EUR for the complete green option per year. Note that we assume the optimistic 2030 case where green hydrogen will be equal to blue and turquoise hydrogen, which is a very supportive assumption regarding green technology. In the worst case scenario of a 30 EUR/MWh difference, the necessary additional subsidies would be 0.5 to 2.7 bn EUR. If we only consider the difference (since we assume the 14 TWh are 100% green and the portfolio approach will only affect the 76 TWh difference) we talk about additional cost of at least 0.76 bn EUR per year. In the worst case, this amounts to 1.5 bn EUR per year. This sounds comparably small, but if we consider 20 years of usage we talk about approx. 15 bn to 30 bn EUR necessary additional subsidies for the 100% green option in the worst case.

3.3. Ressources Bow Wave

Building a modern wind turbine requires a significant amount of metal commodities and rare earths (see Table 2), e.g., about 4–24 t of copper, 430–960 t of steel and at least 0.25 t of rare earth. Besides we need concrete (1650–1950 t) and carbon (30–60 t) which are also subject to capacity constraints but this should be considered as less critical. The exact number varies with the type of the turbine and mainly between offshore and onshore installation. Offshore needs e.g., more copper for cable and more steel for a special underground foundation while onshore typically more concrete is needed. Thus, the above derived number for the base case (energy transformation, green hydrogen of 14 TWh, e-mobility) of turbines would, e.g., induce a demand of 23,000 t copper (all onshore) and 62,000 t (offshore) and 2.1–2.7 Mt special steel. Doing all green would double the numbers (see Appendix A).
Table 2. Commodities demand of windmills based on [42,54] using a direct drive with permanent magnet generator (DD-PMSG) turbine as offshore and a gearbox permanent magnet generator (GB-PMSG) turbine as large onshore representative incl. cables and connection.

| Product         | Demand Onshore/Offshore | Relation       | Purpose                      |
|-----------------|-------------------------|----------------|------------------------------|
| rare earth elements | 0.25–1.9 t per turbine | magnets/generator |
| iron            | 80 t per turbine        | magnets/generator |
| steel           | 430–960 t per windmill  | Everywhere     |
| copper          | 4–24 t per windmill     | Nacelle         |
| zinc            | 22–24 t per windmill    | everywhere      |
| concrete        | 1650–1940 t per windmill| mainly foundation |

In 2019, Germany imported 973,769 t of copper ore (This amount refers to the net imports of ore and concentrates). There are other forms but with comparably smaller amounts) [62]. In total, 276 turbines with 940 MW have been installed, which would mean approx. 3000 t of copper and 0.1 Mt of steel if we assume an equal mix of both types. Thus, only for the installation of the necessary turbines, we would see an increase of the copper imports by approx. 3000–7000 t. This seems comparably small, but note that also wallboxes and grid improvements have to be considered while the effective cooper production has lost momentum in recent years [54].

Note that we only consider the demand for the 14 TWh target, there is still a gap of 75 to 100 TWh to be closed, i.e., generated. If this would be done also by green energy we would increase the demand by a factor of 5, which implies in total up to 9000 t of copper additionally. Even more relevant is the amount of steel. In the past years German production has been on the decline, with a production of about 40 Mt in 2019 [62]. The required amount of steel, approx. 3 Mt, is about 8% of this output, also one should note that most likely a certain part of this demand will be satisfied by foreign supply.

Figures 1–3 aggregate and visually display the results of the bow wave analysis. As expected, the ‘all green’ strategy has the largest effect on all kinds of demand whereas electric mobility contributes only to a minor share of financial or steel demand, for example.

![Figure 1](image-url)
Using an economic model, we want to derive the socially optimal strategy with regards to an investment into hydrogen production as replacement of energy from fossil fuels. The model also considers the impact on resource prices, CO2 emissions, as well as alternative social damage, which allows us to apply it to different new technologies.

We assume that the installation of a production facility for either blue, turquoise, or green hydrogen on average consumes the same amount of copper, steel, and rare earths. Hence, the effects caused by the choice of technology are neglectable for the scope of this analysis. We therefore only focus on the effect of the renewable build-up. For this purpose, a two-stage model for the social optimum is constructed. In Stage 1, a social planner decides how much to invest into different technologies. The planner can invest into new green power generation. The chosen investments then affect the second stage where the social planner decides to produce. Decision variables are the fossil energy input $E$, the input of green hydrogen $W_G$ and the input of natural gas-based (i.e., blue or turquoise) hydrogen $W_{BT}$. We have two stock pollutants, $S_{CO2}$ and $S_{alt}$. $S_{CO2}$ quantifies the effects of carbon dioxide; $S_{alt}$ denotes alternative stock pollutants, here we only consider the solid carbon black from the turquoise hydrogen. Note that storing carbon black has no known significant damage, thus the social-economic damage is considered to be low even for large stocks. Including all mentioned input factors our target function to be maximized equals social consume $C$ minus damage $D$ by the corresponding technology, i.e.,:

$$\begin{align*}
F := C(a_E \times E + a_W \times W, P_R) - D_{CO2}(S_{CO2}) - D_{alt}(S_{alt}) - I_G - I_{BT},
\end{align*}$$

(1)
where

\[
S_{CO_2} = b_E \times E + b_{IG} \times I_G + b_{IBT} \times I_{BT} + b_{BT} \times W_{BT} + S_0,
\]
\[
S_{alt} = b_{aBT} \times W_{BT},
\]
\[
W = W_G + W_{BT}.
\]

This is a standard approach used in environmental economics, where \( C \) is a consume function depending on the energy input and the price level. In order to keep it simple, we use the resource price level \( P_R \) as approximation for the latter variable, which, again, positively depends on the investment level, i.e., \( dP/dI > 0 \). Besides we assume \( dC/dE > 0, d^2C/dE^2 < 0 \), i.e., the consume \( C \) is convex in \( E \). We also assume that \( dC/dP_R < 0 \). These are standard and reasonable assumptions for such types of function. E.g., it makes sense that the consume decreases with an increasing price level. Moreover, \( D_x, x \in \{CO_2, alt\} \), are typical damage functions with \( D'_x, D''_x > 0 \). The factor \( S_0 \) is the initial CO2 stock, although no variable of course it will have an impact for the final weight of the technologies. The factor \( b_x, x \in \{E, IG, IBT, BT\} \), quantifies how much CO2 emissions will result from one unit of energy (E), one EUR of investment into the hydrogen production capacity itself or one unit of blue or turquoise hydrogen. Note that we have also included a factor \( b_{aBT} \) which denotes alternative emissions from blue or turquoise hydrogen. Besides, in Equation (1) \( a_E \) and \( a_W \) denote the efficiency factors of the energy input, since we consider a consume function depending on the efficiency and resources prices \( P, i.e., C\left(\text{eff}, P_R\right) \), where \( E_{eff} \) is the effective energy for consumption. To simplify the model, we assume that the consume level does not affect the resource price level although resources are necessary for the consume. This is an arguable point, but for the scope of our model it will only add complexity without effectively affecting the model’s result regarding the optimal investment levels. Thus, our target variables are the energy input \( E \), and the hydrogen input \( W_{BT}, W_G \). The above-described model is summarized in Figure 4, and all variables are again defined in Appendix B.

**Figure 4.** A two-stage model for deriving the optimal investment decision.

Using Lagrange optimization, the optimal solution on Stage 2 is described by the three derivatives

\[
\frac{dF}{dE} = a_E \times dC/dE - b_E \times D'_{CO_2} + \lambda_E = 0, \quad \text{(3)}
\]
\[
\frac{dF}{dW_{BT}} = a_W \times dC/dE - b_{BT} \times D'_{CO_2} - b_aBT \times D'_{alt} + \lambda_{W_{BT}} = 0, \quad \text{(4)}
\]
\[
\frac{dF}{dW_G} = a_W \times dC/dE + \lambda_{W_G} = 0, \quad \text{(5)}
\]

where \( \lambda_{W_{BT}}, \lambda_{W_G}, \lambda_E \) are the Lagrange multipliers for the energy boundaries. We assume that, in a representative framework, \( \lambda_E = 0 \). Thus \( \lambda_{W_{BT}} - \lambda_{W_G} = b_{BT} \times D'_{CO_2} + b_{BT} \times D'_{alt} \).
Stage 1, again, is about finding the optimal investment into hydrogen production capacities, where we are optimizing Equation (1), i.e.,

$$C(a_E \times E + a_W \times W(I_G, I_BT), P_R(I_G, I_BT)) - D_{CO_2}(S_{CO_2}) - D_{alt}(S_{alt}) - I_G - I_BT,$$

with a budget constraint $I_G - I_BT \leq I_{\text{max}}$. Note that in Stage 2 the factors $S_x, P_R, W_y, x \in \{CO_2, alt\}, y \in \{G, BT\}$, and $E$ (via $W_y$) are basically functions of the investment decision. This is driven by the fact that $W_y$ is a boundary solution and thus $W_y$ and $E$ implicit functions of the investment level, i.e., $W_G = W_G(I_G)$ and $W_BT = W_BT(I_BT)$, respectively. At the same time both $E$ and $S_x$ are uniquely determined by $W_G$ and $W_BT$. Hence, the formulas break down to functions of $I_G$ and $I_BT$

$$\frac{dE}{dI_BT} = \frac{dC}{dP} + \frac{dC}{dE} \left(a_W + a_E \times \frac{dE}{dW_BT}\right) \frac{dW_BT}{dI_BT} - D_{CO_2}' \times b_{IBT} - \left(b_{BT} \times D_{CO_2}' - b_{alt} \times D_{alt}'\right) \frac{dW_BT}{dI_BT} = 1 + \lambda_{IBT} = 0,$$

$$\frac{dF}{dI_G} = \frac{dC}{dP} + \frac{dC}{dE} \left(a_W - a_E \times \frac{dE}{dW_G}\right) \frac{dW_G}{dI_G} - D_{CO_2}' \times b_{IG} - 1 + \lambda_{IG} = 0,$$

with $\lambda_{IG}, \lambda_{IBT}$ being Lagrange factors. We assume, to facilitate a first interpretation, as simplification $dW_BT/dI_BT = dW_G/dI_G$, i.e., the capacity to be installed with one Euro is the same for green and blue/turquoise hydrogen if both are equal and both are similar efficient in producing energy from one m$^3$ hydrogen. This assumption is definitely arguable and in reality we should expect $dW_BT/dI_BT > dW_G/dI_G$, thus one Euro spent in blue/turquoise hydrogen technology induces more hydrogen capacity than one Euro spent in green. To better understand the base mechanism and in order to simplify the equation it is possible, though, now, deducing (9) from (8) we end up with

$$\frac{dC}{dP} + \frac{dC}{dE} \times a_E \times \frac{dE}{dW_BT} \frac{dW_BT}{dI_BT} = D_{CO_2}' \times b_{IBT} - \left(b_{BT} \times D_{CO_2}' + b_{alt} \times D_{alt}'\right) \frac{dW_BT}{dI_BT} = \frac{dC}{dP} + \frac{aC}{dE} \times a_E \times \frac{dE}{dW_G} \frac{dW_G}{dI_G} = D_{CO_2}' \times b_{IG}.$$

If we derive Equation (3) implicitly with respect to $W_BT$ and $W_G$ we yield for $dE/dW_BT$ and $dE/dW_G$

$$\frac{dE}{dW_BT} \left( b_{BT} \times D_{CO_2}' - a_E \times a_W \times \frac{d^2C}{dE^2} \right) = \frac{a_E^2 \times \frac{d^2C}{dE^2} - b_E^2 \times D_{CO_2}'},$$

and

$$\frac{dE}{dW_G} \left( -a_E \times a_W \times \frac{d^2C}{dE^2} \right) = \frac{a_E^2 \times \frac{d^2C}{dE^2} - b_E^2 \times D_{CO_2}'.}$$

Given our assumptions we see that both are negative since all additive terms are negative. This is straightforward, because the more hydrogen we produce, the less conventional energy is needed. Moreover, note that one additional unit of blue or turquoise hydrogen reduces conventional energy demand more than one additional unit of green hydrogen. This is due to the expression $b_{BT} \times b_E \times D_{CO_2}'$ in the numerator of Equation (10), which is missing in Equation (11) and reflects CO2 cross effects.

4.1. The Case of Turquoise Hydrogen

As described in the CO2 bow wave chapter, we assume that turquoise hydrogen has—like green hydrogen—no significant CO2 emissions linked with the generation, which means $b_BT = 0$ and $dE/dW_BT = dE/dW_G = dE/dW$. Thus (9) simplifies to

$$\frac{dC}{dP} + \frac{dC}{dE} \times a_E \times \frac{dE}{dW_BT} \frac{dW_BT}{dI_BT} = D_{CO_2}' \times b_{IBT} - b_{alt} \times D_{alt}' \left( \frac{dW_BT}{dI_BT} = \frac{dC}{dP} + \frac{aC}{dE} \times a_E \times \frac{dE}{dW_G} \frac{dW_G}{dI_G} = D_{CO_2}' \times b_{IG} \right)$$
Our goal here is to show that \( I_{BT} > I_G \). For this we start with \( I_{BT} = I_G = I \) for a moment. Since this must not be the optimal solution, we probably yield an inequality, but we can eliminate at least all terms containing \( dW/dI \) from both sides, i.e.,

\[
\frac{dC}{dP} \frac{dP}{dI_{BT}} - D'_{CO_2} \times b_{IBT} - b_{BT} \times D'_{ahl} \times \left( \frac{dW}{dI_{BT}} \right) < \frac{dC}{dP} \frac{dP}{dI_G} - D'_{CO_2} \times b_{IG}. \tag{13}
\]

Given the recent state of knowledge solid carbon has no marginal social damage at all as long as atomic carbon black can be avoided which we assume. With this assumption Equation (13) is reduced to

\[
\frac{dC}{dP} \times \frac{dP}{dI_{BT}} - D'_{CO_2} \times b_{IBT} < \frac{dC}{dP} \times \frac{dP}{dI_G} - D'_{CO_2} \times b_{IG}. \tag{14}
\]

This is straightforward to analyze. The optimal discussion weights the marginal damage of the CO\(_2\) emissions and the marginal welfare (here consume) loss of the price increase due to the resource need. If one assumes—this of course is up to a deep dive—that the production units (PEMs for electrolysis and plasma bow furnaces for turquoise hydrogen) consume a comparable amount of resources and CO\(_2\) the discussion is only about the necessary green power generation to be installed. Since turquoise hydrogen receives a part of the required energy from natural gas and can utilize the existing production and transport infrastructure, it consumes significant less energy—about 4 times less (see Section 2.1). Therefore \( b_{IBT} < b_{IG} \). For \( I_G = I_{BT} \) we have \( \frac{dC}{dP} \frac{dP}{dI_{BT}} = D'_{CO_2} \times b_{IBT} \), \( \frac{dC}{dP} \frac{dP}{dI_G} = D'_{CO_2} \times b_{IG} \). Therefore, if we slightly increase the investment into turquoise this inequality would still be there. Of course, the term \( dC/dE \times a_E \times dE/\hat{d}I x \in \{G, BT\} \), would reappear and might influence the result. However, as we assume the functions to be continuous, we still can expect inequality in a certain proximity around \( I = I_G = I_{BT} \). Therefore, in equilibrium, we have \( I_{BT} > I_G \). This means that, according to the model, a significant share of turquoise hydrogen would economically help to reduce the wave described and quantified in Section 3. Besides, even if we would expect a small marginal damage of solid carbon, i.e., \( b_{IBT} > 0 \) but small, the model shows that this would not change the bigger picture and \( I_{BT} > I_G \) would still hold. As in the case of green hydrogen generation, turquoise hydrogen generation will be limited and then \( dW/dI \) would decrease rather quickly. Thus, according to the model, for the next 10 to 20 years a mix of both technologies will be relevant. On the medium term the competitive advantage of turquoise hydrogen will decrease, and consequently the share of green hydrogen will increase. Additional exploration and production investments are necessary, which will generate CO\(_2\) emissions and resources demand, however at a reduced level due to the expected decarbonization of industry production. This strategy would distribute the demand over time and would utilize an existing investment, which otherwise, i.e., in case of a 100% green approach, needs to be replaced with additional CO\(_2\) emissions and resource demand. This holds also true if there is a marginal CO\(_2\) reduction effect from switching from turquoise to green. In that case \( \left( b_{BT} \times D'_{CO_2} \right) \times (dW_{BT})/dI_{BT} \) would be added on the left side. Consequently, the “\(<" relationship is not true under all circumstances, but—based on [16]—\( b_{BT} \) will be small. As a consequence, which also is shown by the specific numbers, the all green scenario would imply significant social costs, especially regarding resource needs and investment money. Hence, according to the model, accepting a small amount of more emissions over time is the better choice.

4.2. The Case of Blue Hydrogen

In contrast to turquoise hydrogen, blue hydrogen causes definite CO\(_2\) emissions. Experts estimate that only 90% of the CO\(_2\) resulting from steam reforming can be captured. On the other hand, we have no other damage thus \( b_{IBT} = 0 \). Equation (9) now simplifies to

\[
\frac{dC}{dP} \frac{dP}{dI_{BT}} + \frac{dC}{dE} \times a_E \times \frac{dE}{dW_{BT}} \frac{dW}{dI_{BT}} - D'_{CO_2} \times b_{IBT} - \left( b_{BT} \times D'_{CO_2} \right) \times \frac{dW}{dI_{BT}} - \frac{dC}{dP} \frac{dP}{dI_G} + \frac{dC}{dE} \times a_E \times \frac{dE}{dW_{IG}} \frac{dW}{dI_G} - D'_{CO_2} \times b_{IG}. \tag{15}
\]
If we do the same comparison like in the turquoise case, we learn that it is not a straightforward analysis since the term \( D'_{\text{CO}_2} \times b_{BT} \) appears on the blue side. Let us assume equal efficiency of one invested Euro: If blue hydrogen is given the same investment level its competitiveness depends on (a) the size of the corresponding CO\(_2\) stock and (b) on the efficiency of the CCS procedure. We can assume that the first impact is high, hence we have to talk about the size of \( b_{BT} \). If the CCS procedure is ineffective, blue hydrogen causes too much damage. Besides, due to the higher infrastructure investments like CO\(_2\) pipelines, also the comparably smaller price effect may not be straight forward. In this context, we have to consider two issues: First, in the next 10 to 20 years we should assume \( dW/dI_x \) to be steep thus an efficient investment to reduce CO\(_2\) must spread the money onto different technologies. Second, in case of blue hydrogen it is very likely that the marginal hydrogen production \( dW/dI_x \) is much steeper than in case of green H\(_2\) [8]. Literature estimates that blue H\(_2\) is competitive without substitution in a range of 50 to 60 USD/t CO\(_2\) price [31,63], while even companies like Greenpeace Energy see green hydrogen not competitive without subsidies at a level of 100 USD/t in 2030 [59]. Of course: The higher the initial stock \( S_0 \), the higher the optimal share of green hydrogen, because social costs increase with the size of \( S_0 \). However, even then, one can expect that a quick build up will increase the marginal costs of an additional MWh especially due to a massive increase of the resource costs. As a consequence, blue hydrogen would be an instrument to diversify the problem and dampen the effect.

5. Evaluation of the Results

A key element of a successful green deal is to reduce emissions of heavy industries as quickly and cheaply as possible in order to provide a sustainable pathway for the 100% green technologies. Even if the reduction is only at an extent of 70% to 80% compared to the current levels: Instant reductions tomorrow are better than 100% in 2040 at a costs of ongoing high emission levels tomorrow. On the first glance, it seems logic and necessary to immediately switch to green energy. However, in this article, we have empirically (Section 3 using Germany as an example) and theoretically (Section 4) shown that both regarding time and efficiency this is not the best alternative—even if it would be technically and financially possible to ramp up the necessary green capacity (wind mills, hydrolyzer, etc.) quickly, something which is questionable anyhow given the numbers derived here.

Tables 3 and 4 illustrate the involved number when assuming that the gap between the minimum H\(_2\) target for Germany in 2030 and the minimum green H\(_2\) target is closed by turquoise instead of green hydrogen. The resulting bow wave reduction is significantly, simply because we reduce the necessary number of renewable generation. While one can discuss whether it is realistic that all generation is by wind and therefore there will be some portfolio effect in terms of energy mix reducing the bow wave (note that switching to solar power may reduce the steel demand, but it is replaced by silicon and silicon production is fairly energy and CO\(_2\) intensive, thus the relaxation potential in terms of CO\(_2\) and resources demand is small), a large share of additional green energy generation for Germany will be wind-based. Thus, for the 75 TWh of H\(_2\) production needed in case of green H\(_2\) we can assume that the power will be generated by wind turbines. The amount of money (Tables 3 and 4) as well as the additional bow wave effects are large. If we can reduce this by three-quarters due to also CO\(_2\)-neutral turquoise hydrogen, which utilizes the existing gas infrastructure, we can mitigate large parts of the effect.
If the use of turquoise (and also of blue) hydrogen is focused on the decarbonization of steel, concrete, and silicon production, something which is a logical step also from the technical point of view, the CO$_2$ bow wave effect of the future green build-up can be reduced significantly. This timeline effect has been already described in literature [6] and where turquoise hydrogen is referred to as ‘bridge technology’. However, it is more than a bridge technology as we intend to show here. We need this H$_2$ alternative also as an enabler for future green hydrogen and energy production as well as simply for diversification to reduce both resources and financial demand as much as possible. As mentioned above this implies the use of natural gas in combination with CCS and turquoise hydrogen as an infrastructure saving option. Green hydrogen should, in a first step, be considered in areas where no access to a modern gas grid is possible or sufficient green energy is not available.

### 6. Conclusions

In this article, we evaluate the implications of introducing green hydrogen to the economy using Germany as an example. For this purpose, we conduct an empirical study to calculate the consequences for financial and resource demands, for example. Thereby, we come to the conclusion that focusing only on green hydrogen will induce a significant bow wave of different dimensions: There is no doubt that solving the urgent CO$_2$ emission problem will induce a massive investment in order to decarbonize the industry and to switch—at least in the midterm—to green hydrogen as well as fuels and chemistry which are based on it. However, the question is when—i.e., how quickly—to invest. On the one hand, a quick build-up helps to reduce production costs of green hydrogen significantly and induce the necessary research and development efforts. On the other hand, as shown in this article, it induces a massive bow wave in the three dimensions CO$_2$, invest costs and resources. A simple but not often applied diversification approach shows that a purely green strategy cannot do it alone without causing significant bow waves. Even if we initially ignore the intertemporal aspects, we see that we can significantly reduce social cost and therefore speed up CO$_2$ reduction by using all ‘colors’ of hydrogen. As long as the CO$_2$ levels are not critical it is—according to our calculations—reasonable to boost the reduction by using the 80% clean solution which is blue hydrogen. Moreover, turquoise hydrogen, which—considering the process itself—is CO$_2$ free, can support green H$_2$ by utilizing the existing natural gas grid. This color of hydrogen has the potential to reduce the bow wave effects induced by the green power generation by $\frac{3}{4}$. On the intertemporal timeline using these technologies to decarbonize the necessary industries will initially support the build-up of green capacities and reduce the bow wave at the same time. This all fits to the view that fossil-based clean or emission-reduced technologies are considered to be bridge technologies. With the expectation that green technologies will be competitive without any subvention between 2040 and 2050 [37,38]—i.e., 20–30 years—this is also efficient. With

#### Table 3. Costs of green and turquoise hydrogen for type 1 onshore turbines.

| Scenario Type 1 | No. Turbines | EUR (bn) | Copper Mt | Steel Mt | Concrete Mt | CO$_2$ Mt |
|-----------------|--------------|---------|-----------|----------|-------------|-----------|
| Demand green 14 TWh | 1429 | 6.29 | 0.01 | 0.61 | 2.36 | 3.31 |
| Demand all green | 9184 | 40.41 | 0.03 | 3.93 | 15.17 | 21.27 |
| Demand 76 TWh turquoise | 2296 | 10.10 | 0.01 | 0.98 | 3.79 | 5.32 |
| Reduction due to turquoise | 6888 | 30 | 0.02 | 3 | 11 | 16 |

#### Table 4. Costs of green and turquoise hydrogen for Type 2 offshore turbines.

| Scenario Type 2 | No. Turbines | EUR (bn) | Copper Mt | Steel Mt | Concrete Mt | CO$_2$ Mt |
|-----------------|--------------|---------|-----------|----------|-------------|-----------|
| Demand green 14 TWh | 658 | 14.21 | 0.02 | 0.63 | 1.28 | 4.00 |
| Demand all green | 4229 | 91.35 | 0.10 | 4.04 | 8.22 | 25.71 |
| Demand 76 TWh turquoise | 1057 | 22.84 | 0.03 | 1.01 | 2.06 | 6.43 |
| Reduction due to turquoise | 3172 | 69 | 0.07 | 3 | 6 | 19 |
the given and fixed green build-up targets till 2030 there are already enough incentives for research and development efforts and a hydrogen market build-up. From an industry economics point of view, it is not a bridge but the next technology generation. This means that the next generation of industrial technology is not green but colorful (at least blue and turquoise).

In this situation, substantial further research needs to be done. Assuming that efficient technology will be the bottleneck in the next years a specific investment strategy regarding time and place is required: which sector should be addressed first, especially if we consider the impact on later green investments described in this paper? Which locations are most suitable for the first sites and which technology option would be the most efficient one? Which of these sectors have their key emissions within the EU and can be decarbonized easily? These questions become even more important if infrastructure issues and transportation are included. An interesting issue is thereby the decarbonization of shipping considering that for long-range vessels a fuel switch is unlikely in the next 10 to 20 years. Last but not least, in order to perform a more detailed analysis, our model can be extended to an investment model in a competitive market with environmental instruments.

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**Appendix A. Specifications for Two Artificial Turbine Types**

We calculate with an annual runtime of 3500 h onshore and 3800 h offshore, which are slightly optimistic but still realistic assumptions in industry. Based on [42] and available data for typical up-to-date wind turbine types like Nordex N149, Vestas V164, Haliade-X etc. we construct two model wind turbine types, namely Type 1 (onshore) and Type 2 (offshore). Their parameters are given in Table A1.

**Table A1. Offshore vs. onshore turbines—a summary of costs and resource demand.**

| Type                  | Type 1 (Onshore) | Type 2 (Offshore) |
|-----------------------|------------------|-------------------|
| GWh/year              | 14               | 30                |
| Full load hours       | 3500             | 3800              |
| MW                    | 4                | 8                 |
| Million EUR per MW    | 1.1              | 2.7               |
| Cost Turbine + Installation + Fee | 4.4 | 21.6 |
| Copper incl. Cable (t) | 4                | 24                |
| Steel (t)             | 428              | 956               |
| Concrete (t)          | 1652             | 1944              |
| Carbon composite (t)  | 34               | 65                |
| Nickel (t)            | 0.96             | 1.92              |
| Zink (t)              | 22               | 44                |
| rare earths (t)       | 0.248            | 1912              |
| CO₂ (t)               | 2514.08          | 6080              |
| g CO₂/kWh             | 8.27             | 10                |

The amount of g CO₂/kWh in Table A1 correspond to the numbers mentioned in recent studies [37,64–67] where the value here is taken from the average calculated in [37].
Facts and fundamentals show that offshore wind, for example—due to the use of ships and higher amount of steel and copper—is slightly more intensive. Based on the given literature, we assume 10 g CO$_2$/MW. We use information from the Irena Study [30] as baseline for the costs. Using an 2020 exchange rate of 1.2 EUR/USD we yield 1.1 million EUR/MW for onshore and 2.7 million EUR/MW for offshore installations.

**Appendix A.1. Demand Energy Transition**

In 2019, direct power generation in Germany was 243 TWh whereof 107 TWh was due to renewable sources. If we first ignore effects from electric mobility and green/turquoise hydrogen, it is reasonable to assume that the demand will stay rather constant (or increase) i.e., around 240 MW. The European Energy Exchange, a virtual energy exchange, expects a share of renewables of at least 65% in 2030, i.e., on the 2019 levels we would need approx. 157 TWh. i.e., a gap of approx. 50 TWh to be filled until 2030. With our assumptions, we yield the numbers displayed in Table A2.

Table A2. Demand for the energy transition in terms of onshore/offshore turbines.

| No. Turbines | bn EUR | Copper (Mt) | Steel (Mt) | Concrete (Mt) | CO$_2$ (Mt) |
|--------------|--------|-------------|------------|---------------|-------------|
| Type 1       | 3571   | 15.71       | 0.01       | 1.53          | 5.90        | 8.27        |
| Type 2       | 1645   | 35.53       | 0.04       | 1.57          | 3.20        | 10.00       |

**Appendix A.2. Demand Electric Mobility**

We assume that the number of electric vehicles will be small cars (for using downtown) with an demand of 158 KWh/100 km and a 10,000 km/year (this is an average value, but considering e.g., the VW ID.3 fairly realistic [42]). If we assume 10 Mio cars in use until 2030 for Germany, we yield a demand of in total 15.8 TWh power which can be assumed to be additional since the energy for refining gasoline typically is taken from oil or gas. Table A3 summarizes the result.

Table A3. Demand for the electric mobility in terms of onshore/offshore turbines.

| No. Turbines | bn EUR | Copper (Mt) | Steel (Mt) | Concrete (Mt) | CO$_2$ (Mt) |
|--------------|--------|-------------|------------|---------------|-------------|
| Type 1       | 1129   | 4.97        | 0.0004     | 0.48          | 1.86        | 2.61        |
| Type 2       | 520    | 11.23       | 0.0125     | 0.50          | 1.01        | 3.16        |

**Appendix A.3. Demand Green Hydrogen**

In the German H$_2$ strategy a green H$_2$ target of 14 TWh in 2030 with an energy demand of 20 TWh is stated—i.e., an average efficiency of 70% is assumed. The total demand is seen between 90 to 110 TWh. For our calculations of the 100% green scenario, we choose the lower boundary, i.e., the 90 TWh. Based on this numbers we calculate turbine numbers, steel demand etc. for two cases, namely for the 14 TWh scenario (Table A4) and the 90 TWh scenario (Table A5).

Table A4. Demand for green hydrogen (14 TWh) in terms of onshore/offshore turbines.

| No. Turbines | bn EUR | Copper (Mt) | Steel (Mt) | Concrete (Mt) | CO$_2$ (Mt) |
|--------------|--------|-------------|------------|---------------|-------------|
| Type 1       | 1429   | 6.29        | 0.0005     | 0.61          | 2.36        | 3.31        |
| Type 2       | 658    | 14.21       | 0.016      | 0.63          | 1.28        | 4.00        |

Table A5. Demand for green hydrogen (90 TWh) in terms of onshore/offshore turbines.

| No. Turbines | bn EUR | Copper (Mt) | Steel (Mt) | Concrete (Mt) | CO$_2$ (Mt) |
|--------------|--------|-------------|------------|---------------|-------------|
| Type 1       | 9184   | 40.40       | 0.034      | 3.93          | 15.17       | 21.27       |
| Type 2       | 4229   | 91.35       | 0.101      | 4.04          | 8.22        | 25.71       |
### Appendix B. List of Variables Used in The Economic Model

| Variable(s) | Definition |
|-------------|------------|
| $I_G, I_{BT}$ | Investment into green hydrogen ($I_G$) or blue/turquoise hydrogen ($I_{BT}$) |
| $E$ | fossil energy input |
| $W_{BT}, W_G$ | hydrogen input depending on the production type, where $G =$ green hydrogen and $BT =$ blue or turquoise hydrogen |
| $S_0, S_{CO_2}, S_{alt}$ | $S_0$ denotes the initial CO$_2$ stock; $S_{CO_2}, S_{alt}$ are the stock amounts of CO$_2$ and solid carbon black |
| $C$ | consume function |
| $D_{CO_2}, D_{eff}$ | damage functions due to CO$_2$ or solid carbon black |
| $b_T, b_{BT}, b_G, b_{BT}$ | emission factors of the respective energy and emission type |
| $h_{BT}$ | alternative emission factor of the respective energy type |
| $a_{e,qW}$ | efficiency factors for fossil energy (E) and hydrogen (W) |
| $E_{eff}$ | effective energy consumption |
| $R$ | resource prices |
| $\lambda_{W_{BT}}, \lambda_{W_G}, \lambda_{E}, \lambda_{S}, \lambda_{BT}$ | Lagrange multipliers |

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