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Sector Coupling Potential of Wind-based Hydrogen Production and Fuel Cell Train Operation in Regional Rail Transport in Berlin and Brandenburg.

eingereicht von: Sebastian Herwartz

Gutachter/innen: Prof. Dr. Tobia Lakes

Dr.-Ing. Stephan Schmid

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Sector Coupling Potential of Wind-based Hydrogen Production and Fuel Cell Train Operation in Regional Rail Transport in Berlin and Brandenburg

Sebastian Herwartz

Humboldt-Universität zu Berlin

Geographisches Institut

Angewandte Geoinformationsverarbeitung

And

Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR)

Institut für Fahrzeugkonzepte

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Abstract

In recent years, the concept of decarbonizing the transport sector using wind-based hydrogen as a means of sector-coupling has been widely discussed. In Germany, after 2020, wind park operators will gradually cease to receive subsidies for a large share of the installed onshore wind power, as funding is limited to 20 years. For many windmills it is unclear, whether a profitable operation without funding is possible. Furthermore, the remaining diesel operated rail passenger service is ought to be largely decarbonized. Since track-side electrification is expensive and associated with complex and time-consuming approval procedures, using fuel-cell powered trains could be a viable alternative. Whether it is possible to use energy from track-adjacent aged windmills to provide hydrogen for these trains is currently in discussion.

In this study I assess the regional potential of on-site wind-based hydrogen as a substitute to diesel in regional rail transport using a GIS approach in conjunction with a site-level cost model. For this, I consider windmills ceasing to be eligible for the public funding feed-in compensation and diesel operated regional passenger train networks in the region of Berlin and Brandenburg, Germany.

Hydrogen unit production costs mainly depend on the potential hydrogen consumption volume, the site locations and the available adjacent wind power. The costs are estimated considering capital and operational expenditures for electrolysis, compression, storage and distribution, the length of potential pipelines and electric transmission cables, landscape-related costs and financing costs.

Due to a combined 10.1 million annual diesel-fueled train kilometers resulting in an estimated overall diesel consumption of 7.3 million liters, a hydrogen demand of 1982 annual tons could be generated. Until 2030, 4100 MW of installed wind power capacity will cease to receive EEG feed-in compensation, of which 1004 MW are unlikely to experience repowering for legislative and administrative reasons.

Hydrogen production costs of approximately 6.35 €/kg can be achieved on favorable sites. Assuming a future price decrease and efficiency increase for water electrolysis, hydrogen costs of 6 €/kg and below could be achieved on annually 6.27 million train kilometers with an overall annual hydrogen consumption of 926 tons. These results suggest that hydrogen could add to decarbonizing the public transport sector in Germany.

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Abbreviations and acronyms

HRS	Hydrogen Refueling Station
DMU	Diesel Multiple Unit
FCEMU	Fuel Cell Electric Multiple Unit
P2G	Power-to-Gas
AEL	Alkaline Electrolysis
PEM	Polymer Electrolyte Membrane
EEG	Erneuerbare-Energien-Gesetz
WEG	Windeignungsgebiete
ROG	Raumordnungsgesetz
GIS	Geographic Information System
BEW	Bundesverband Windenergie e. V
PDC	Percentage Doldrums Coverage
VBB	Verkehrsverbund Berlin Brandenburg
Capex	Capital Expenditures
Opex	Operational Expenditures
ODEG	Ostdeutsche Eisenbahn GmbH
GBER	General Block Exemption Regulation

Units of measure

kW	Kilowatt
kWh	Kilowatt hour
MW	Megawatt
MWh	Megawatt hour
Kg	Kilogramm
T	Metric ton
Train-km/a	Annual train kilometer
Ton-km	Ton-kilometer
€	Euro

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1 INTRODUCTION

Hydrogen based sector coupling is widely regarded as an important part of the German 'Verkehrswende' and 'Energiewende', integrating and decarbonizing both the energy sector and the transport sector.

Hydrogen transportation and infrastructure in Germany is currently developing. There are 75 hydrogen refueling stations (HRS)[1] available for individual road traffic in Germany. The government's aim is to establish 400 HRSs until 2038[2]. Additionally, there are several pilot schemes operating bus lines on hydrogen.

About 54 % of the German rail network is not electrified[3]. On those non- or partly electrified tracks, diesel fueled trains (diesel multiple units – DMU) are operated. Those could potentially be replaced with hydrogen powered trains (fuel-cell electric multiple unit – FCEMU). In 2018 the world's first FCEMU was set in scheduled passenger service in Germany[4,5]. Recently, several more pilot schemes for hydrogen rail transport have been publicly announced[6–8]. Meanwhile, hydrogen-fueled train operation remains an exception in German rail transport.

Hydrogen is used for a large variety of industrial applications. The most widespread method to produce industrial hydrogen is steam reforming[9] where hydrogen is extracted from natural gas. Through its dependence on natural gas, this method generates approximately 10 tons of carbon dioxide per ton hydrogen[9]. Fossil free hydrogen can be produced with water-electrolysis if the electrolysis is powered by renewable energy sources. Recently this has often been done in the context of power-to-gas applications (P2G). A well-known electrolysis technology is the alkaline electrolysis (AEL). However for P2G applications polymer electrolyte membrane (PEM) electrolysis is considered more suitable due to its potential high power density and the possible partial load operation[10]. Compared to AEL which is the most mature electrolysis technology PEM is a relatively new technology and therefore more cost intensive than AEL. With increasing market penetration, the prices (and efficiencies) of PEM systems are expected to decrease[11]. So far, water electrolysis systems showed efficiencies between 40 % and 66.5 % (resp. 6.5 to 4.5 kWh/Nm³)[10,12].

To decarbonize rail transport with hydrogen, the energy for electrolysis has to be produced fossil free. The major source for renewable energy in Germany is on-shore wind power with a share of 15.4 % of the German gross electricity consumption[13]. In the scope of the German Renewable Energy Sources Act[14] ('Erneuerbare-Energien-Gesetz' - EEG), from 2000 onwards newly constructed wind mills (and plants constructed before 2000) were warranted a 20 year feed-in compensation ('EEG-Umlage'). In the upcoming years, many windmills will become ineligible to receive EEG-compensation and in many cases further operation will be unprofitable[15] due to low energy market prices. When possible, operating companies usually choose to repower plants in order to operate on higher efficiency. Between 2003 and 2018, dedicated wind power regions (Windeignungsgebiete - WEG) in appliance with the Federal Regional Planning Act (Raumordnungsgesetz – ROG[16]) were assigned in Brandenburg[17–21]. According to ROG, plants erected outside those assigned regions can only continue to operate but cannot be repowered. It is often said, that new alternative schemes for direct marketing of electricity need to be developed to keep these old plants profitable[22]. Using these particular plants to provide energy for water electrolysis would be such an alternative use. In this scenario, windmill operation could be independent from low market prices while regional rail transport could be decarbonized using locally produced wind-energy.

There has been profound research on (renewable) P2G-technologies, discussing the technological and economic state of the art of water electrolysis[10,12,23–28]. In those studies, the role of excess energy for P2G is often discussed and besides P2G other concepts such as power-to-heat and power-to-fuel are usually considered[29]. Even though these studies often cover energy system analysis, the main study focus is usually on the technological state and the economic possibilities. Spatial factors are rarely included.

For hydrogen infrastructure, namely hydrogen pipelines[30] and hydrogen refueling stations[31], several studies implemented geographical methods, namely geographic information systems

(GIS) in their rather economic approaches[32–40]. However, those studies mainly focus on individual road transport and operate on national level. Most studies derive possible hydrogen consumption loads from varying demographics and evaluate pipelines and other hydrogen transportation modes between regional centers.

Recent work in hydrogen rail transport was often commissioned by public federal governments and is mostly published as project reports. These publications are often in the scope of feasibility studies on project scale[41] or of entire federal states[42,43] evaluating the general economic and technological potential. Spatial analysis in this field is rare. The hydrogen considered in these studies does not necessarily originate from fossil free sources.

The Federal Association for Wind Energy (Bundesverband Windenergie e. V – BWE) has commissioned an analysis on windmill operation after 2020[15] projecting further operation as economic unfeasible at the current market prices. They project minimal operating costs for aged windmills at approximately 0.03 €/kWh, making a market-bound operation unprofitable.

In this study, I present a novel approach for estimating the sector coupling potential of wind-based hydrogen production and regional rail passenger transport. I exemplarily conduct this approach on the region of Berlin and Brandenburg, Germany. To the best of my knowledge, no work has been done estimating this potential on regional scale, assuming renewable hydrogen from local wind energy, especially none combining technological, economical and spatial factors. I conduct this study in three steps according to the following main objectives: (i) the assessment of the potential hydrogen consumption of the regional rail passenger transport, (ii) the assessment of suitable rail-adjacent wind power and (iii) the evaluation of suitable sites for on-site electrolysis including an assessment of the costs of hydrogen production relative to the potential demand, production and site location.

2 METHODOLOGY

2.1 Approach

The analytical approach of this study is organized as shown in Figure 1, structured according to the three main objectives stated above. First, I conduct a GIS-based assessment of the current DMU-operation in the study region (box 1, fig. 1). For this purpose, I pre-select FCEMU-suited train lines and research vehicle types, distances and circulations from which I derive the current diesel consumption and the potential hydrogen consumption. After quantifying the hydrogen potential, I localize current diesel refueling stations and determine further possible spots for hydrogen refueling stations. In the second step (box 2, fig. 1), I assess the current wind power plants in operation and determine plants suitable for coupled hydrogen production. Therefore, I select windmills, test if they are part of a wind park (wind park affiliation) and exemplarily analyze energy yields for the reference years 2014-2016. In the third step (box 3, fig.1) I create potential sites for electrolysis, using a spatial overlay technique and I calculate the specific hydrogen production costs for each potential site, based on a developed cost model which takes the hydrogen potential, the wind potential and the distances and route characteristics between the different wind parks and HRSs into account. Finally, I perform a sensitivity analysis of the cost calculation. An overview of the used input data can be found in appendix C.

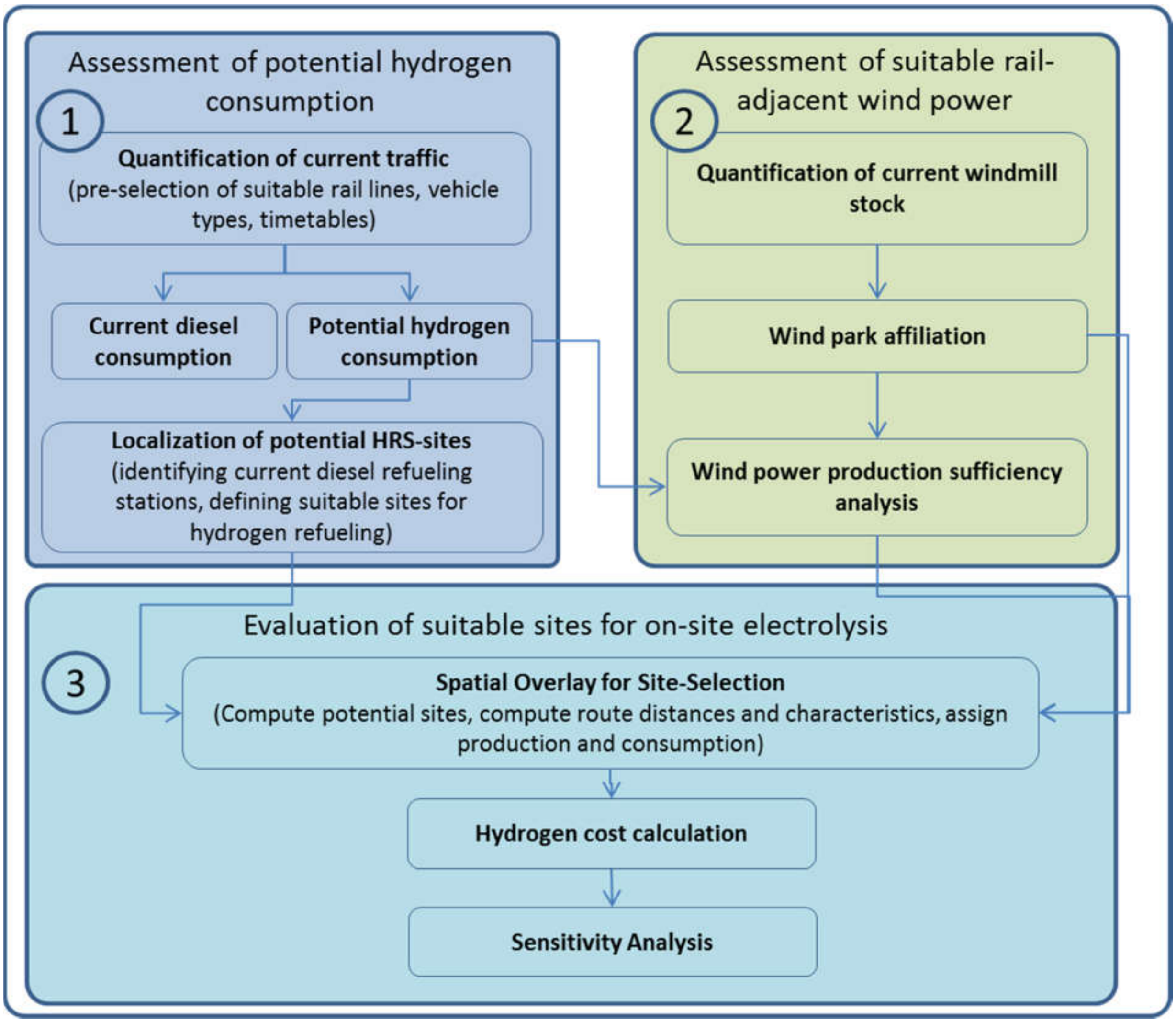

Figure 1: Analytical Approach

2.2 Scope

For power production, I exclusively consider wind power. I consider all windmills in Brandenburg (standing stock). Because windmills outside of WEGs cannot be repowered, these are of special interest for alternative marketing schemes and will be considered in addition to the standing stock. For hydrogen consumption I exclusively consider the current DMU-operated regional rail passenger service. The plant concept used in this study is shown in Figure 2. Wind parks will deliver electric energy through transmission lines to a hydrogen production plant, consisting of a stacked electrolyzer, a compressor plant and a high-pressure multi-day storage. The high-pressure hydrogen will be transported from the production plant via pipeline to a HRS.

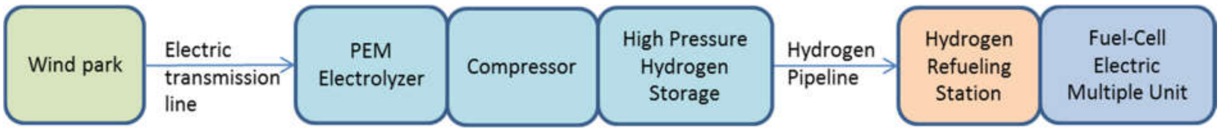

Figure 2: Hydrogen production chain concept.

This isolated off-grid plant scheme is necessary since it is crucial to stay disconnected from the electricity grid in order to avoid network charges and other EEG restrictions[14]. Therefore, the hydrogen storage must be adequately designed to ensure full hydrogen coverage at all times.

The study region considered is the region of Berlin and Brandenburg. In this region, about 2650 km of railway tracks exist from which 732 km are not electrified. Several million train kilometers annually are operated with DMU in Brandenburg with an ascending trend of passengers in the region[44]. Considering wind power, the federal state of Brandenburg is the second largest producer of wind energy in Germany[45] with an installed capacity of almost 7000 MW in 2016. Brandenburg's minister of economic showed a clear commitment to renewable hydrogen by presenting strategic cornerstones for the development of hydrogen technologies in the energy, heat and transport sectors[47]. Due to the high population density, there is no considerable wind power installed in Berlin.

2.3 Assessment of potential hydrogen consumption

The methodology for assessing the hydrogen potential is conducted in two steps. First, the current traffic is quantified and the potential hydrogen consumption is derived accordingly. In a second step, the spatial locations of where hydrogen could be consumed (i.e. the hydrogen refueling stations) are determined.

2.3.1 Quantification of current traffic

To quantify current DMU-bond railway transport, I pre-selected all DMU-operated railway lines which are in operation and which are used for passenger railway service. If one of the following points applied, railway lines were considered as not well suited for analyzing FCEMU potential and were therefore excluded from further analysis:

- The track is assigned as priority need for track-side electrification in the federal transport plan for 2030 ('vordringlicher Bedarf im Bundesverkehrswegeplan')[48].

- The track is known to be electrified.
- The not-electrified parts of the track are combined shorter than 10 km (in this case, an operation with battery driven trains is far more reasonable).
- The majority of the track-length is outside of Brandenburg.

A more specific description of the excluded railway lines is given in appendix A. The vehicle types, routing and daily train kilometers were specified throughout a research in tender documents and operator publications[49]. The circulation was derived from the timetables of the network operators[50–52] and was averaged over the whole week and year to form a daily average.

The average daily diesel consumption was derived using the standardized methodology to evaluate investments in traffic infrastructure commonly used in Germany[53]. According to this procedure, the vehicle specific diesel consumption per km b can be estimated with

$$b_D = \frac{W_k * e}{1000} \quad \textbf{(1)}$$

where e is the diesel consumption per 1000 ton-kilometers (see Table 1) and

$$W_k = W_{k,zero\ load} + W_{k,passenger} + W_{fuel} \quad \textbf{(2)}$$

with $\boldsymbol{W_{k,zero\ load}}$ being the weight of the empty train $\boldsymbol{k}$ (see Table 2), $W_{k,passenger}$ the average weight of the passengers and W_{fuel} the weight of the diesel load. The passenger weight can be calculated as

$$W_{passenger} = S_k * u * w_{passenger} \quad \textbf{(3)}$$

with S_k being the number of seats of train k, u being the average utilization rate in regional rail passenger service and $w_{passenger}$ the average passenger weight.

The daily diesel consumption of the considered train line B_D were then computed with

$$B_D = b_D * D_d \quad \textbf{(4)}$$

where D_d represents the daily driven kilometers. The potential daily hydrogen consumption B_{H2} was derived from the iLint specific consumption b_{H2} (0.23 kg H2/km[43,54,55]), since this is the only available vehicle on the market. The daily hydrogen consumptions were calculated with:

$$B_{H2} = b_{H2} * D_d \tag{5}$$

Diesel and hydrogen consumptions were calculated for each railway line.

Table 1: Parameters for calculating average diesel consumption according to the standardized methodology to evaluate investments in traffic infrastructure[53].

Parameter	Symbol	Value
Diesel consumption per 1000 ton-km	e	10.1 l/km
Average diesel weight	W_{fuel}	1000 kg
Average utilization rate (occupied seats)	u	0.28
Average passenger weight	$w_{passenger}$	75 kg

Table 2: DMUs operated in the study region[49].

DMU	Seats	$W_{k,zero\ load}$ [t]
Stadler RS 1 (BR 650) (1 car)	70	40
Bombardier Talent (BR 643) (3 car)	156	96,5
PESA LINK (BR 632) (2 car)	140	95
LVT/S - BR 502/504	69	32
Double-deck BR 670	78	34,25
Alstom Coradia LINT 41 (BR 648)	120	68
Stadler GTW (BR 646)	100	73,3
Lint 27	61	41
Siemens Desiro (BR 642)	124	69

The estimated diesel consumption does not take the actual passenger utilization into account. Instead a fixed value per seat is used (compare equation (3). The influence of passenger numbers however is low. Table 3 exemplarily shows the diesel consumptions of a DMU with various passenger utilization rates.

Table 3: Diesel consumption of a 1-car Lint27 with a net mass of 41t.

Passenger utilization (seats occupied)	Diesel consumption [l/km]
No passengers	0,41
28 %	0,44
100%	0,49

2.3.2 Localization of potential HRS-sites

To determine suitable sites for hydrogen refueling, I first determined sites at where the installation of HRS sites do not require alterations in the current circulation. Therefore, I mapped the locations of existing diesel refueling stations[56,57] used for passenger railway service and identified train stations where longer breaks (exceeding one hour) in passenger operation occur (trains cannot be fueled while passengers are on board) or where trains could be refueled before or after operating hours. I derived those locations from the public timetables. Based on insight of the Brandenburg railway system, I identified additional train stations suitable for hydrogen refueling.

The selected sites were collectively added to a base layer (hereafter HRS base sites). Since refueling stations are often not located directly at the train stations themselves but are often in the vicinity of them, I created a two kilometer buffer around the base sites. Within this buffer I set points in a 250 meter distance on each railway track available (including industrial tracks and tracks where no DMU`s operate). These points represent potential HRS sites (see Figure 3). I then assigned the aggregated potential hydrogen consumption of the underlying DMU-train connections to each potential HRS.

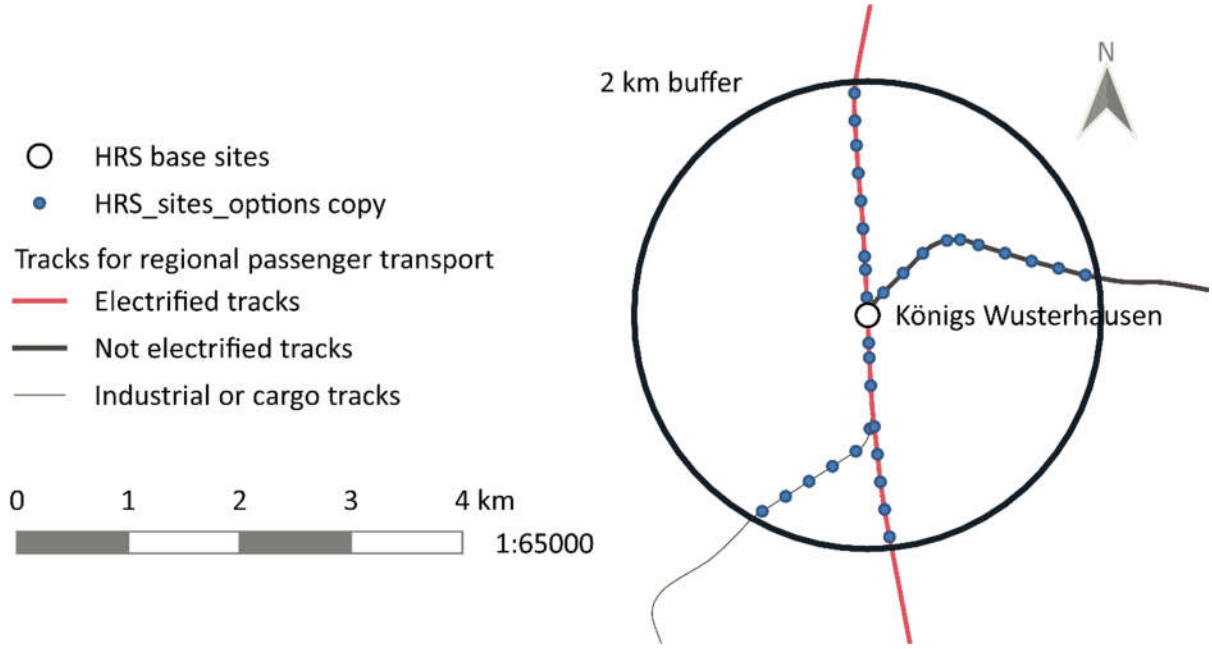

Figure 3: Construction of potential HRS-Sites.

2.4 Assessment of suitable rail-adjacent wind power

After quantifying the potential hydrogen consumption, I assessed the energy provision needed to produce renewable local hydrogen. I conducted this in three steps: the assessment of the current stock of windmills, the affiliation of windmills to wind parks and the evaluation whether sufficient hydrogen could be provided with local wind power.

2.4.1 Quantification of current windmill stock

From the complete windmill stock of Brandenburg, I exclusively selected windmills in operation since I only consider the standing stock. I then selected all windmills outside the WEG's, adding a 100-meter buffer around the wind region layer to account for inaccuracies due to scaling issues (the layer is only legally reliable on a scale of 1:100.000). The further analysis was then carried out for both, the windmills outside the WEGs and the whole running windmill stock.

2.4.2 Wind park affiliation

Since the risk of plant failure is high for single windmills, only windmills which are part of a wind park are considered as suitable. I affiliated windmills to wind parks using a kernel density estimation and empirically determined a 0.7 kernel density raster value as a threshold for wind park affiliation. A detailed description on how the kernel density estimation was performed and how the threshold was determined can be found in appendix A. Neighboring cells with a raster value larger than 0.7 where aggregated and transferred to vector polygons representing wind parks. For each affiliated wind park, I aggregated the rated capacity of the specific windmills.

2.4.3 Wind power production sufficiency analysis

I tested wind park sufficiency by assessing whether a wind parks power production can provide sufficient hydrogen throughout the year and therefore ensure uninterrupted FCEMU-operation. I performed this test for several consumption loads (250-1500 kg/d) using modeled wind park load curves[58] based on MERRA2- reanalysis data[59] for the years 2014 - 2016. This period was chosen because these were the latest years available in the model data. Earlier years weren't considered due to restrictions in computational power.

I selected wind parks (from the data set produced prior) with varying locations, rated capacities, hub heights and turbine types. For each wind park, I calculated the percentage of days where production doldrums would lead to an insufficient hydrogen provision (percentage doldrums coverage - PDC). In order to calculate the PDC, I simulated hydrogen storage levels assuming storage capacities of three-, five-, seven- and ten-day storages, with:

$$level_{k,i} = \begin{cases} level_{k,i-1} + P_{H2} - H2_d, & level_{k,i-1} + P_{H2} - H2_d < H2_d * k \\ H2_d * k, & else \end{cases} \quad \textbf{(6)}$$

where $level_{k,i}$ is the level of the hydrogen storage for size k at time i and $H2_d$ the daily hydrogen consumption in kg/d and P_{H2} the possible daily hydrogen production (derived from the wind park output). The level represents the level of the exploitable tank volume, meaning that the minimum level in the storage tank at which hydrogen can be delivered equals to zero in the simulation. The initial load ($level_{k,i=0}$) is assumed to be fifty percent of the maximum load, calculated as:

$$level_{k,i=0} = \frac{H2_d * k}{2} \quad \textbf{(7)}$$

The PDC was then calculated with:

$$PDC = \frac{D}{N} * 100\% \quad \textbf{(8)}$$

Where N is the sum of days over the reference period and D is the number of days where hydrogen provision is insufficient (i.e. $level_{k,i} \leq H2_d$). A detailed discussion of the PDC evaluation can be found in Appendix B.

2.5 Evaluation of suitable sites for on-site electrolysis

In the final step of analysis, I identified potential sites for electrolysis and calculated the site-specific costs. The developed cost model was evaluated with a sensitivity analysis in order to validate the model approach and to take possible future adaptions of costs into consideration.

2.5.1 Spatial overlay for site-selection

To determine potentially suitable sites for electrolysis, I buffered the HRS site layer (see 2.3) and the wind park layer (see 2.4) with a buffer distance of seven kilometers, rasterized the vector data sets (pixel size 250 m) and intersected the resulting arrays (see Figure 4). The seven kilometer long distance was derived by a project, similar to the plant concept described in section 2.2 which is currently in preliminary planning (anonymous personal communication, July 17, 2019).

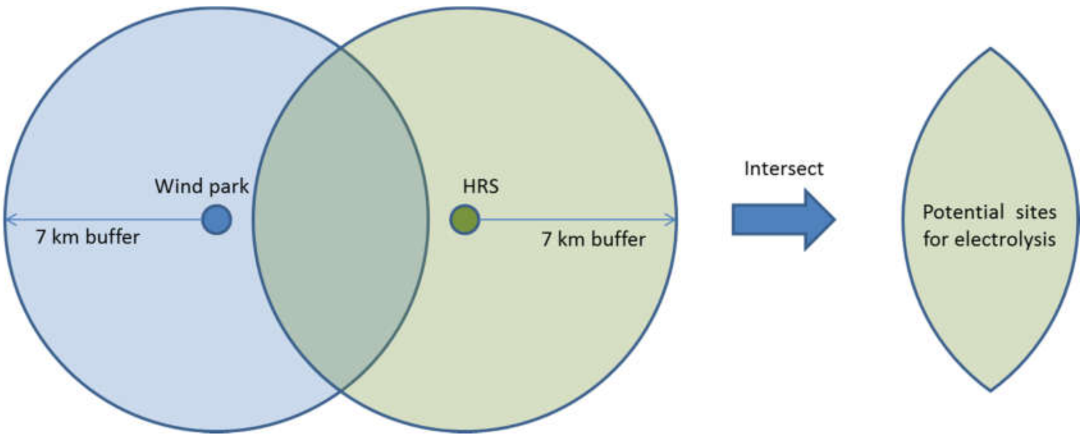

Figure 4: Geoprocessing for determining suitable areas for electrolysis.

I then subtracted constraints (residential areas, protected areas, water bodies; for further information see appendix C) from the resulting raster data (see Figure 5). The resulting layer forms the area in Brandenburg generally suitable for hydrogen production. The raster dataset was vectorized. Around each pixel center a polygon with the same edge length as the pixel size (250 m) was constructed.

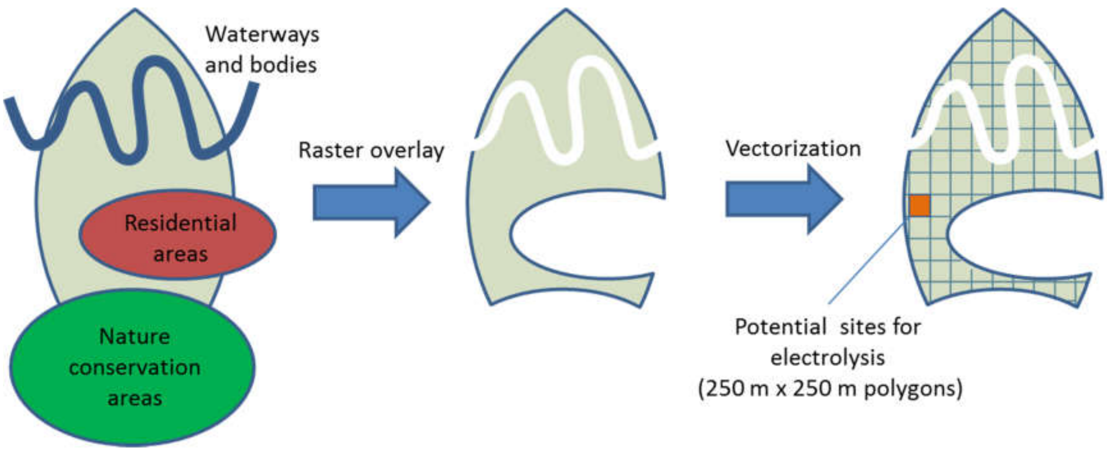

Figure 5: Geoprocessing for determining suitable sites for electrolysis.

For each polygon, I performed a nearest neighbor analysis determining the closest HRS site. The resulting hydrogen consumption was multiplied with the minimum rated capacity (24 kW/kg, see section 3.2.3 and appendix B). The nearest wind park with the corresponding minimum capacity was then assigned. The specific rated capacity and the potential daily hydrogen consumption as well as the according linear distances were assigned as attributes to each polygon. As a proxy for the landscape type, I used the infrastructure density. For this I counted the intersections of a line (forming the linear distance between each polygon and the specific wind park/HRS) to roads and waterways and assigned the number of intersections to each polygon.

2.5.2 Hydrogen Cost Calculation

I developed a cost model to calculate costs of hydrogen production and delivery. For this, I calculated capital expenditures (capex) and operational expenditures (opex) for each module shown in Figure 2. Hydrogen costs are calculated in Euro per kilogram (€/kg). For the energy content of hydrogen, I assumed a lower heating value of 33.3 kWh/kg. For the capex calculations I assumed a governmental investment cost funding of 45 % (compare appendix A), a 1.8 % interest rate[60] and 2.75 % of the capex for additional project costs[61] such as tender related expenditures, legal expenditures and land rents. Furthermore, I assumed 3500 annual hours of electrolysis[11,43,62] and a power density of 54 kWh_{electr}/kg_{H2}[10].

The cost of hydrogen C_h is calculated with the sum of the funded annual capex $C_a(f)$ where f is the funding rate, O_a the annual opex, I_a annual financing costs and P_a the annual project costs, divided by the annual hydrogen consumption $H2_a$:

$$C_h = \frac{C_a(f) + O_a + I_a + P_a}{H2_a} \quad \textbf{(9)}$$

C_a is computed with

$$C_a = \sum \frac{C_k}{l_k} \quad \textbf{(10)}$$

where C_k is the capex of module k and l_k its specific lifespan (see Table 4).

Table 4: Lifespans of plant modules[12,27,29,30,36,42,43,63–66].

Plant module	Lifespan l	Unit
Windmills	20	[a]
Electric transmission line	20	[a]
Electrolyzer Stacks	15	[a]
Electrolyzer System	25	[a]
Compressor	15	[a]
Hydrogen Storage	30	[a]
HRS	20	[a]
Pipeline	40	[a]

The module specific capex's are calculated as follows. The capex for the compressors, storages and HRSs are computed with:

$$C_k = c_k * H2_d \quad \textbf{(11)}$$

with c_k as the module specific capex rate and $H2_d$ the average daily hydrogen consumption. The capex for pipelines and electric transmission cables are computed as follows, with

$$Ck = \left(c_{min}^{k} + \frac{c_{max}^{k} - c_{min}^{k}}{6} * I_k\right) * D_k * d \tag{12}$$

where c_{min}^{k} is the specific minimum cost per meter and c_{max}^{k} the maximum cost per meter, D_k the specific length of the transmission and d a detour factor (comp appendix A), redeeming nonlinear cable/pipeline routings. Capex for electrolysis C_{el} is computed with:

$$C_{el} = C_{System}^{el} + \frac{H2_d * PD * c_{stack}}{h_{el}} \tag{13}$$

with C_{System}^{el} being the fix capex system costs (e.g. for auxiliary plants such as heat exchanger, pumps, gas separators, etc.), PD the power density of the PEM-electrolyzer (Table 7) and c_{stack} the specific capex investment rate in € per kW.

Table 5: Capex and Opex cost parameters[12,27,29–34,36,38,42,43,63–71].

Plant module		Symbol	Value	Unit
Capex electrolyzer	Stack rate	c_{stack}	1000	€/kW
	System	C^{el}_{System}	2,000,000	€
Capex compressor			5000	€/kg hydrogen
Capex hydrogen storage			2935	€/kg hydrogen
Capex HRS[31]			5000	€/kg hydrogen
Capex	Min		100	€/m
Electric transmission line	Max		500	€/m
Capex Pipeline	Min		350	€/m
	Max		1500	€/m
Opex Windmills		o_W	0.0285	€/kWh
Opex elc. trans. line			2.5	%/a of spec. capex
Opex electrolyzer			3.5	%/a of spec. capex
Opex compressor			4	%/a of spec. capex
Opex hydrogen storage			2	%/a of spec. capex
Opex pipeline			4	%/a of spec. capex
Opex HRS			5	%/a of spec. capex

The annual opex is computed as follows

$$O_a = \sum (C_k * o_k) \tag{14}$$

where o_k is the specific opex rate for module k. The only exception forms the opex calculation for the windmills O_w, which is computed as

$$O_w = H2_a * PD * o_W \tag{15}$$

with o_W as the specific operating cost per kWh (€/kWh). Yearly financing costs I_a and yearly project costs P_a are computed with:

$$I_a = \sum(C_k) * i * f \qquad \textbf{(16)}$$

$$P_a = C_a * p \qquad \textbf{(17)}$$

with i as the interest rate and p as the project cost rate.

Table 6: Consecutive cost parameters[60,61,72,73].

Cost	Symbol	Value	Unit
Public funding rate	f	45	% of annual capex
Interest rate	i	1.80	%/a of overall capex
Additional project costs	p	2.75	%/a of annual capex

Table 7: Properties electrolyzer[10,11,43].

Name	Symbol	Value	Unit
Power density electrolyzer	PD	54	kWh/kg
Daily operating hours electrolyzer	h_{el}	9.6	h

2.5.3 Sensitivity analysis

In order to test the sensitivity of the cost model and to determine which parameters influence the hydrogen production costs the most, I conducted a sensitivity analysis for capex, opex, wind power opex, PEM stack costs, annual operating hours of the electrolyzers and efficiencies for the electrolyzer. With these parameters, I emphasized the sensitivity analysis on the costs of electrolysis. Therefore, I tested each parameter on how they influence the hydrogen costs by gradually changing the input parameters between $\pm$ 50 %.

3 RESULTS

In the following sections I will present the results of the performed analysis. Supplemental information in appendix A might add to a better understanding of the presented results.

3.1 Assessment of potential hydrogen consumption

3.1.1 Quantification of current traffic

In the study region, there are 2470 km of railway tracks used for passenger rail service from which 732 km are not electrified (Figure 6). On 1.211 km of the railway tracks DMUs are in operation. On 732 km DMUs are operated under catenary (e.g. Eberswalde – Prenzlau) or on not-electrified side-tracks (e.g. Stendal-Rathenow). There are eight railway networks where DMUs are operated. Within these eight networks, there are 21 DMU-operated railway lines which sum up to 12.2 million train-km yearly. In six of these networks, on 14 lines within, FCEMU-operation is generally feasible according to the assumptions in 2.3.1. These lines sum up to 867 km in length (648 km non-electrified) and 10.1 million train-km/a (of which 2.5 million are driven under catenary). On these railway lines, 0.72 million ton-km are tackled annually, of which 0.2 million ton-km are carried under catenary. The currently used DMU types are shown in Table 2 in section 2.3.1. In the following sections, I will exclusively consider the FCEMU-suited railway lines, referring to them only as railway lines.

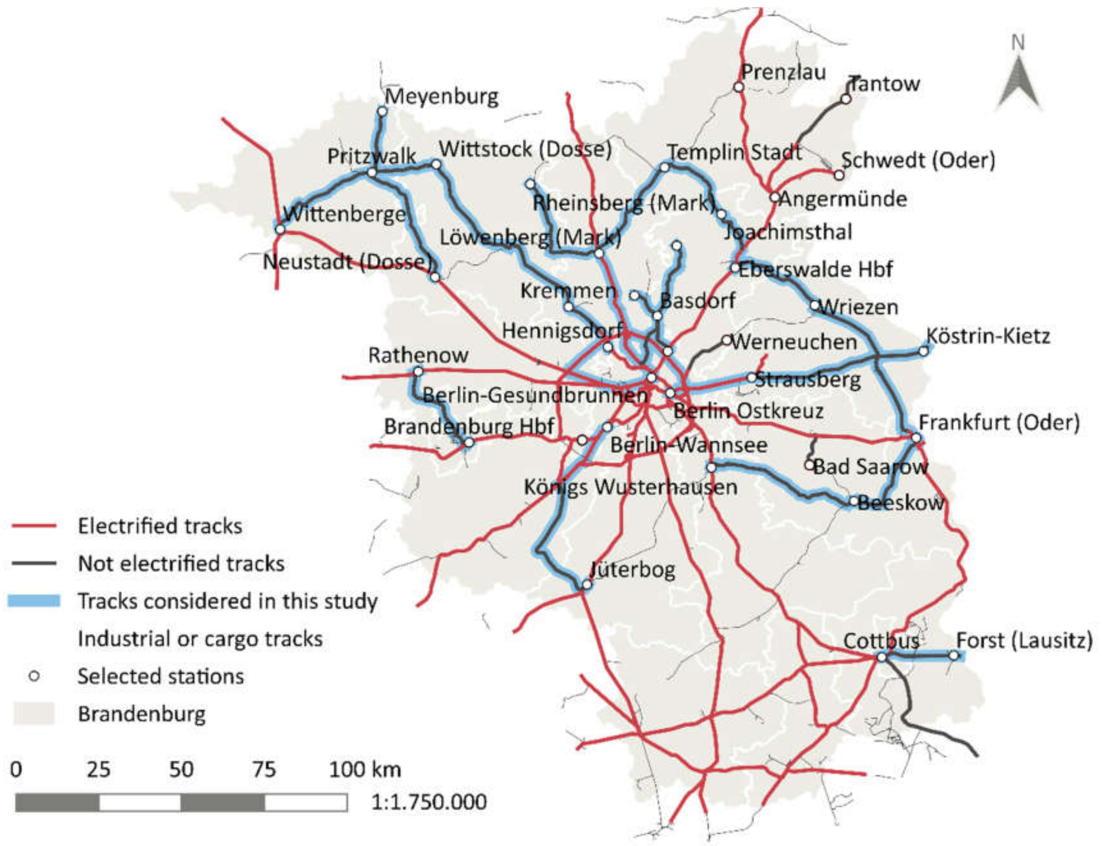

Figure 6: Railroad tracks in Berlin and Brandenburg.

For the assessment of the current traffic performance, I evaluated the public timetables but not the circulation plans of the train operators due to a lack of availability. It is likely that higher diesel and hydrogen consumptions would result, if the circulation would be considered, because circulations include additional trips for fueling, maintenance and vehicle transfer. Since it remains unclear, how the operational modes of the various train operator companies vary, this additional traffic load cannot be approximated using a simple factor. To avoid an overestimation of traffic and to keep the workflow reproducible for other regions, I only considered the trips derived from the timetables. However, when comparing the computed annual train-kilometers with the values provided by the regional transport association (Verkehrsverbund Berlin Brandenburg – VBB, see Table 8) the quantification of the traffic seems adequate. The difference at 'Stadtbahn II' is due to the fact that the VBB provides the train-km for the whole network, including trains operating on electrified tracks.

Table 8: Comparison of annual train kilometers.

Railway network	VBB Mill. train km/a[49]	Calculated Mill. train km/a
Ostbrandenburg	5	4.751
Prignitz	0.2	0.295
Nordwestbrandenburg	2.4	2.579
Heidekrautbahn	0.7	0.940
Stadtbahn II	7 (mainly electrified)	1.250
Spree-Neiße	1.9	0.323

3.1.2 Current diesel and potential hydrogen consumption

According to the steps described in 2.3.1, I estimated an annual diesel consumption of 7.3 million liters (i.e. 6105 tons) for all considered networks. On average, the diesel consumption is 0.64 l/km. The highest diesel consumption of 1638 thousand liters/a appears on RE6 between Berlin Gesundbrunnen and Wittenberge, the lowest (28 thousand liters/a) on RB74 between Pritzewalk and Meyenburg.

Hydrogen consumptions are calculated as potentially achievable consumptions assuming that the complete train operation on a line is switched to FCEMU. In the following I refer to it as hydrogen consumption. The annual hydrogen consumption accounts to overall 1982 tons. The highest consumption per rail line is 458 t/a (RE6) and the lowest 16.2 t/a (RB74). An overview of the diesel and hydrogen consumptions by network is shown in Table 9. For better comparison, the diesel consumption is given in tons.

Table 9: Annual diesel and hydrogen consumptions of DMU/FCEMU grouped by tendered railway networks.

Network	Diesel consumption [t/a]*	Hydrogen consumption [t/a]
Ostbrandenburg	2734	929
Prignitz	83	58
Nordwestbrandenburg	1515	504
Heidekrautbahn	780	184
Stadtbahn II	790	244
Spree-Neiße	203	63

*(Diesel = 0.84kg/l)

3.1.3 Localization of potential HRS-sites

Overall, there are 19 existing base-HRS sites and 601 potential HRS sites (Figure 7) in the study region, meaning that an average of 31.6 potential HRS-sites per base-site were created. The average hydrogen consumption per potential HRS is 248 t/a, the median consumption 206 t/a.

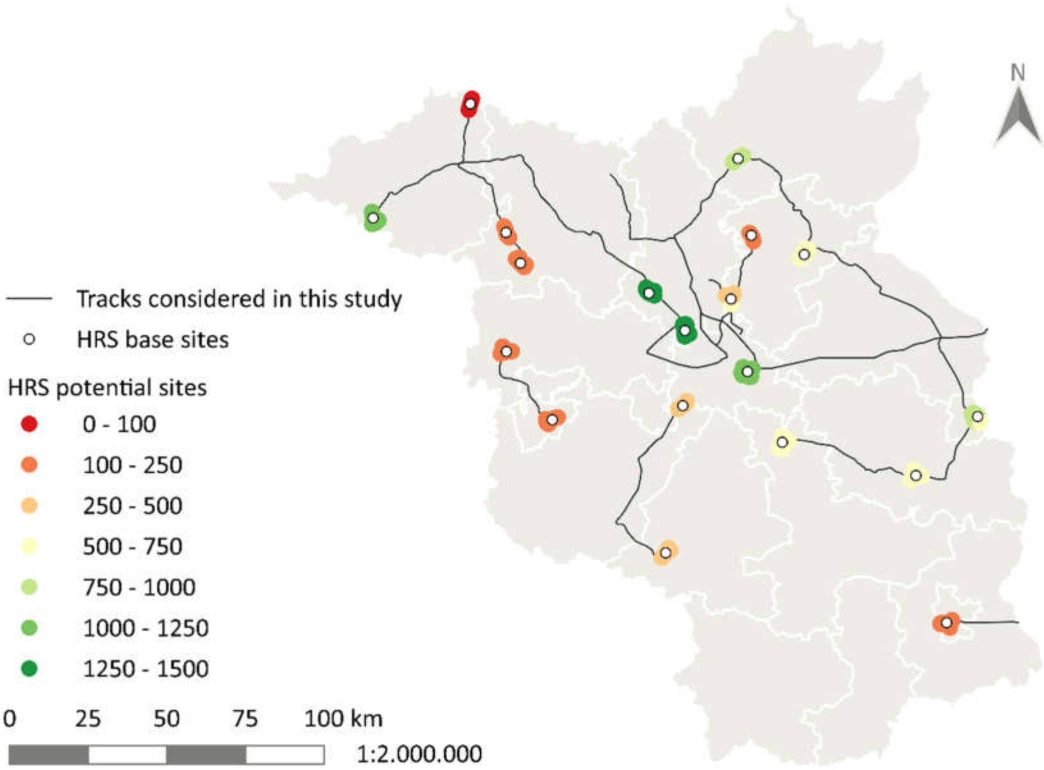

Figure 7: HRS sites.

3.2 Assessment of suitable rail-adjacent wind power

3.2.1 Quantification of current windmill stock

As of December 2018, there are 3772 operational windmills in the study region with an aggregated rated capacity of 6934 MW (see Figure 8a). On average, the plants have a rated capacity of 1.84 MW (median = 2.0; standard deviation = 0.776). The plant stock outside WEG consists of 916 windmills with an aggregated capacity of 1358 MW (see Figure 8b). On average, the plants have a rated capacity of 1.48 MW (median = 1.5; standard deviation = 0.74). This shows that older turbines usually have smaller capacities than younger turbines.

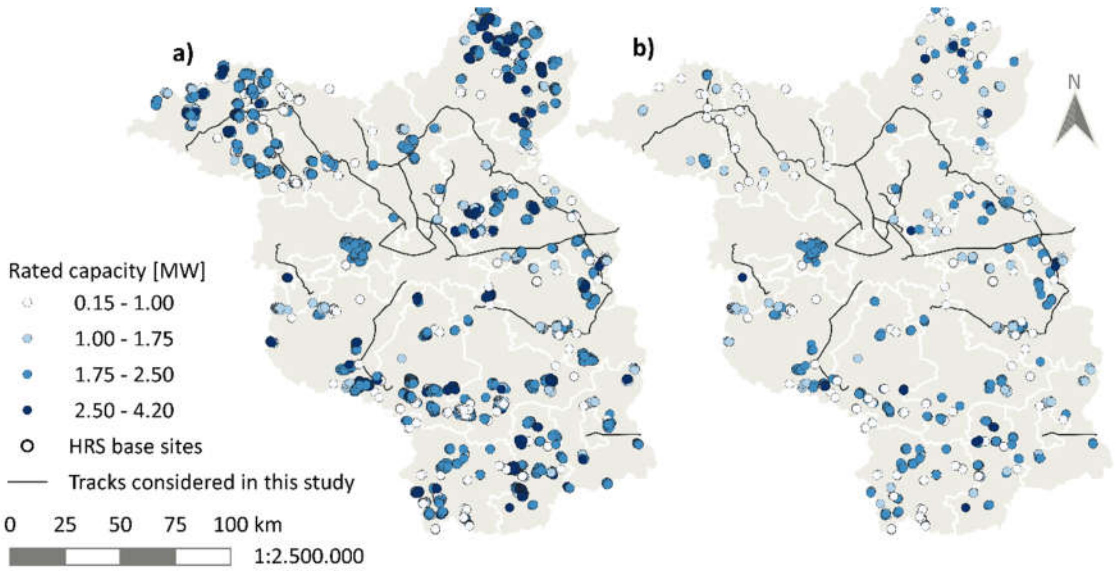

Figure 8: Windmills in Berlin/Brandenburg. a) Standing stock b) Standing stock outside wind regions (WEG).

Figure 9a shows the distribution of the plant age for the reference year 2019, showing that only since EEG-compensation is available (year 2000), windmills are erected on a broader scale. Figure 9b shows the trend to larger turbines over time due to advancing technology[61].

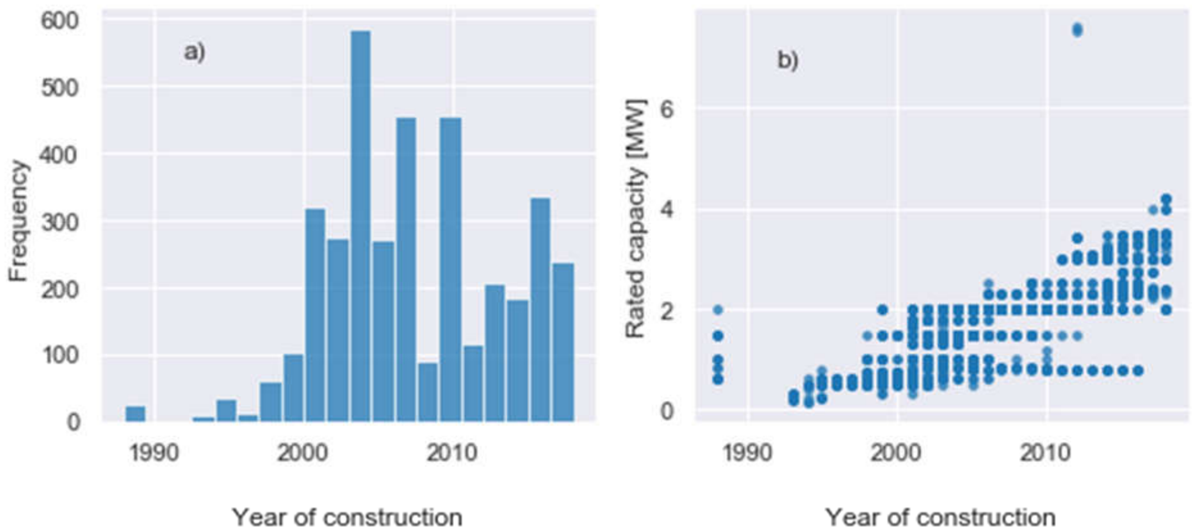

Figure 9: Windmills standing stock: a) Year of construction b) capacity-age-curve.

Figure 10 shows the wind power capacity becoming ineligible to receive EEG-compensation. In 2020, 165 windmills with a rated capacity of 240 MW will become ineligible from which 104 MW are located outside WEGs. Annually about 365 MW will become ineligible on average (71 MW for windmills outside WEGs). Until 2030, 4100 MW of installed wind power capacity will cease to receive EEG feed-in compensation of which 1004 MW are located outside WEGs.

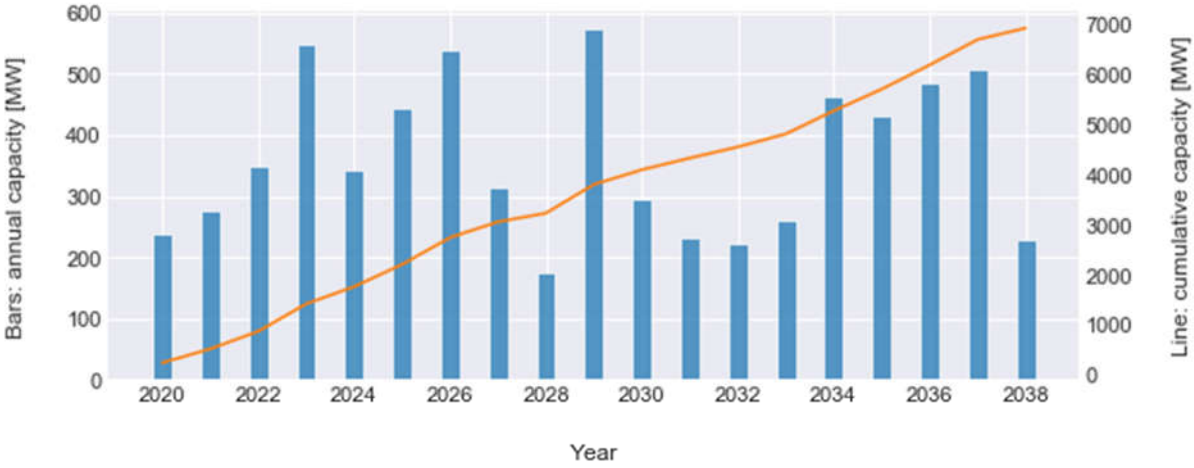

Figure 10: Plants becoming ineligible to receive EEG-compensation.

3.2.2 Wind park affiliation

For the complete windmill stock, I affiliated 214 wind parks reaching an overall rated capacity of 6873 MW (Figure 11a). For the plant stock outside WEG, I affiliated 136 wind parks with an aggregated rated capacity of 988 MW (Figure 11b).

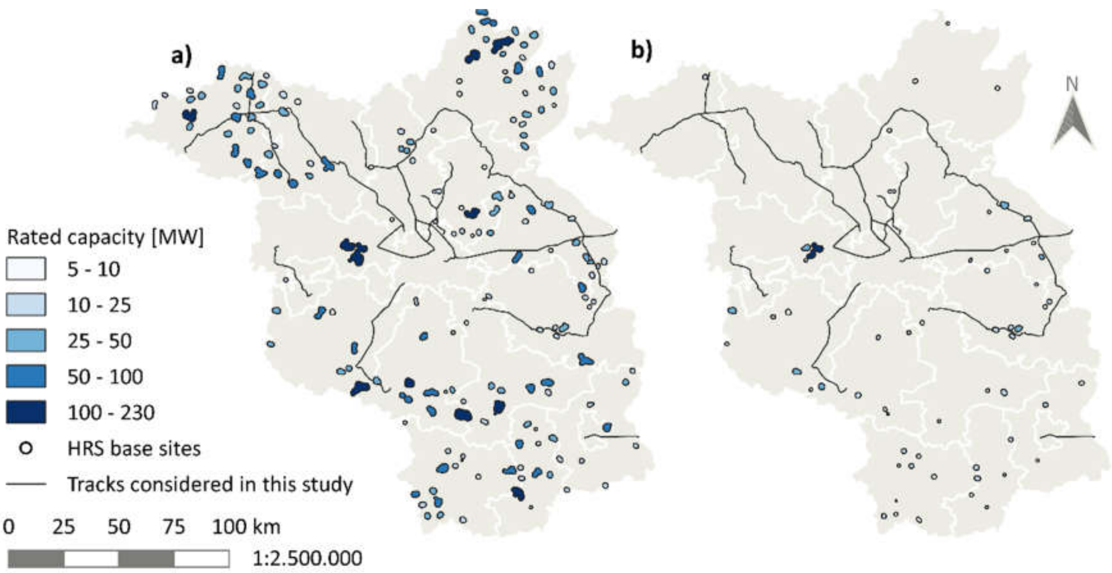

Figure 11: Wind parks affiliated: a) Standing stock b) Standing stock outside wind regions (WEG).

3.2.3 Wind power production sufficiency analysis

The PDC was computed exemplarily for 12 wind parks with diverging characteristics (an overview of all wind parks considered can be found in appendix B). A PDC of 99 % means that on up to 11 days over the three reference years (one percent of 1095 days), the energy produced with those wind parks would not have provided enough hydrogen for FCEMU-operation. Thus, an external hydrogen delivery would be necessary. An example is shown in Figure 12: With a 10.5 MW wind park and a 5-day storage capacity, a hydrogen consumption of 650 kg/d can be covered at all times during 2016 (which translates to a PDC of 100 %).

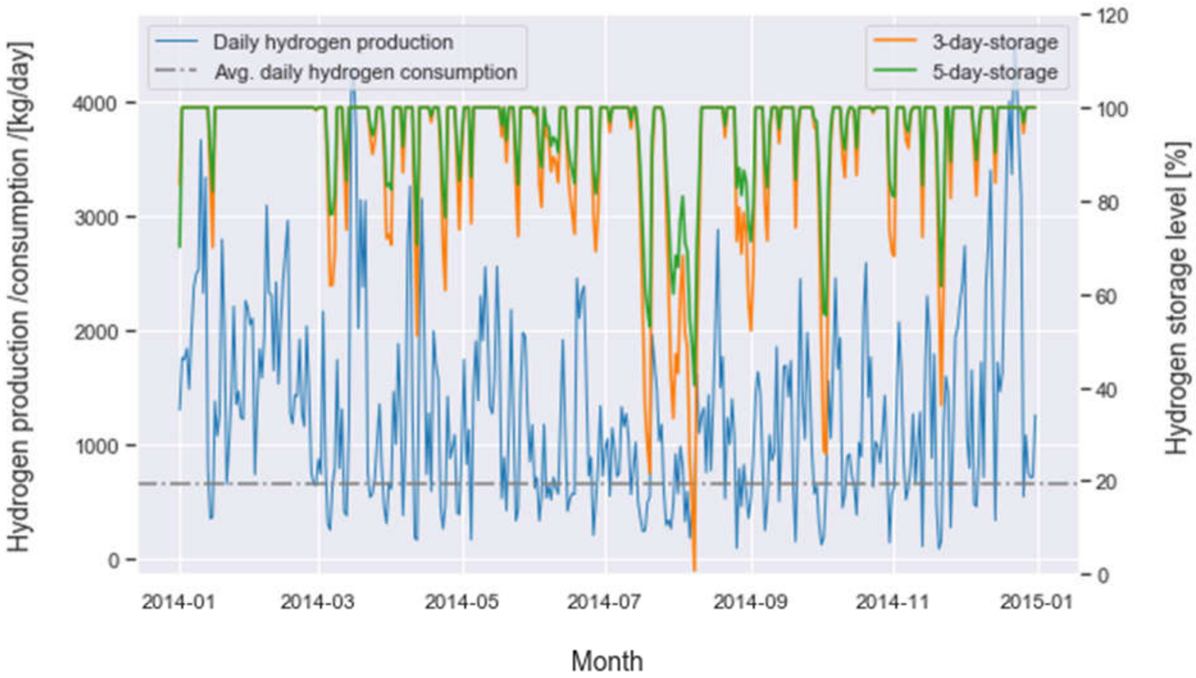

Figure 12: Hydrogen production and simulated storage levels for a wind park at Frankfurt (Oder), for the year 2016. Assumed hydrogen consumption: 650 kg/d.

From the empirical assessment of the 12 wind parks, I derived a threshold value on how much capacity is needed to provide a certain amount of daily hydrogen consumption. Figure 13 shows that the estimated empirical value of 24 kW rated wind power capacity per kilogram hydrogen a day is sufficient to ensure a PDC of 100 % (assuming a 5-day storage). For a train line with a hydrogen consumption of 250 kg/d this corresponds to a necessary rated wind power capacity of 6000 kW. It should be stated, that this is an empirical value, which can deviate locally for various reasons. Also, it should be noted that the threshold of 24 kW/kg is derived from a PDC of 100 % for all tested wind parks meaning this value ensures that there is a year-round sufficient hydrogen provision, guaranteeing an operation without additional hydrogen delivery. A more detailed description on how the threshold was derived is shown in appendix B.

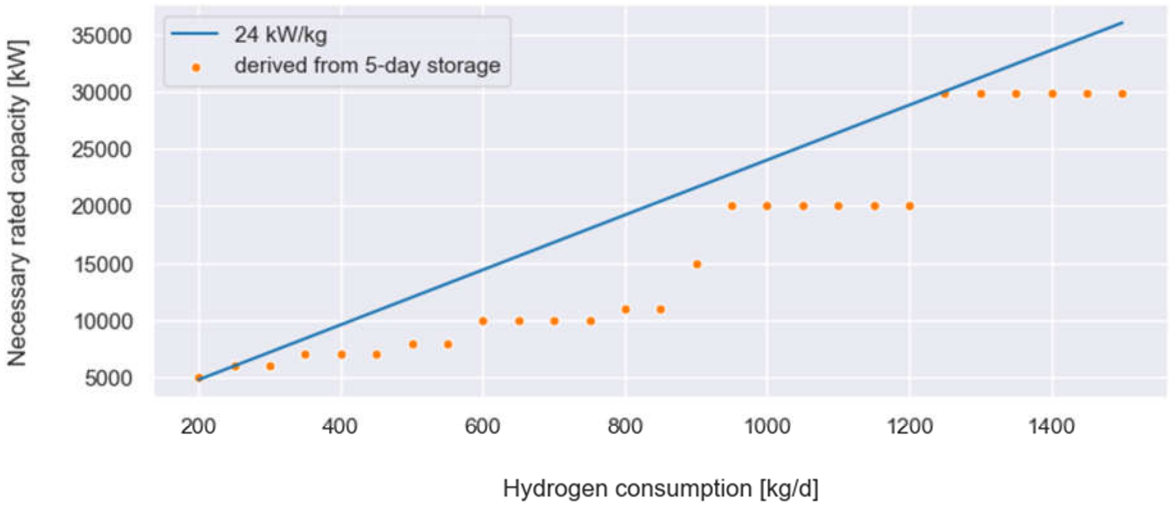

Figure 13: Derived necessary rated capacity per daily hydrogen consumption for a 5-day storage capacity.

Using 24 kW/kg often leads to an overproduction in most times of the year (compare Figure 12 and the discussion in section 4.2.2). A larger storage could help to reduce the necessary rated capacity. I tested for varying storage capacities (3-day ,5-day ,7-day and 10-day storage capacities) the needed rated capacity. I found the highest effect on the necessary installed wind park capacity between a 3-day storage and a 5-day storage. The mean necessary rated capacity per daily kg hydrogen is shown in Table 10. Since I found that the change rate between 3-day and 5-day storages is the largest, I assumed a 5-day storage capacity for further analysis.

Table 10: Average minimal necessary rated capacity.

Storage capacity	Mean of the necessary rated capacity [kW/kgH2$_d$]	Δ Mean rated capacity [kW/kgH2$_d$]
3-days	21.4	
5-days	18.5	2.94
7-days	16.9	1.49
10-days	15.8	1.18

3.3 Evaluation of suitable sites for on-site electrolysis

The results for 2.5.1 and 2.5.2 will be presented together in the following section.

3.3.1 Site selection and cost calculation

The parameter with the largest effect on the hydrogen costs is the daily hydrogen demand. Figure 14 shows the relation between the two parameters for a representative model plant with a three-kilometer pipeline and a one-kilometer transmission cable. The diagram shows that with increasing consumptions, costs decrease non-linearly, with the costs converging upon a threshold defined by other cost parameters.

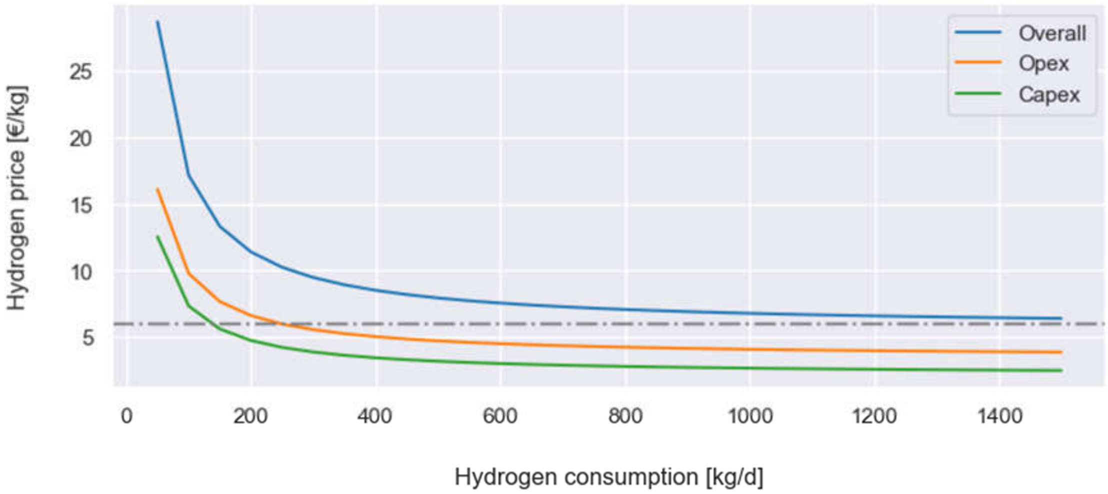

Figure 14: Cost-production ratio for a model plant (pipeline: 3km, 3 intersections; transmission cable: 1km, 3 intersections).

A cost of six euros per kilogram hydrogen is widely considered as a threshold for profitable operation[11,37,42]. Hydrogen costs of 6 €/kg and below can be achieved with a hydrogen demand of at least 1200 kg/d at favorable locations (pipeline 500 m, 0 intersections; transmission cable 500 m, 0 intersections). On sites which require longer pipelines and/or transmission cables, costs below six euros are unlikely. The lower the hydrogen demand, the stronger its effect on the costs, and vice versa. The effect of the distance parameters (pipeline length, transmission cable length and the landscape type represented by the infrastructure density) on the production costs are shown in Figure 15 and Figure 16.

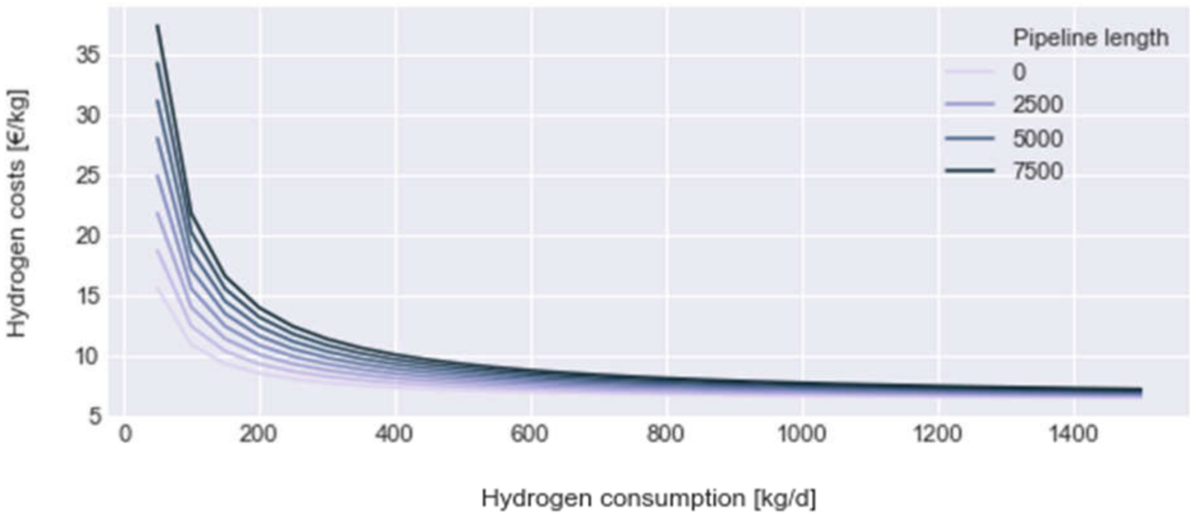

Figure 15: Effect of pipeline length on hydrogen production costs (pipeline: 3 intersections, transmission cable: 1 km, 3 intersections).

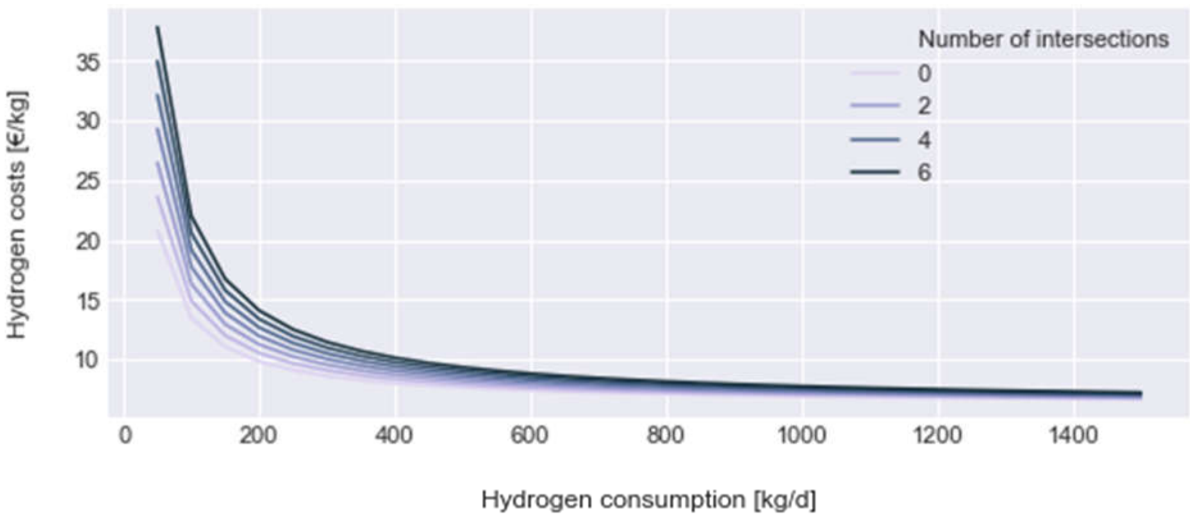

Figure 16: Effect of pipeline intersections on hydrogen production costs (pipeline: 3 km, transmission cable: 1 km, 3 intersections).

As stated above, costs of six euros per kilogram hydrogen are widely considered as a threshold for profitable operation[11,37,42]. In the recent literature, PEM stack costs and system costs are expected to decrease until 2030[11,25,25,37,74]. Additionally PEM efficiencies are expected to increase[10–12]. Figure 17 shows the calculated hydrogen costs for a plant with a 500 m pipeline with no intersections and a 500 m transmission cable with no intersections. Assuming a stack price decrease of 50 % and an electrolysis efficiency increase of 25 % and a system capex decrease of 25 %, hydrogen costs of 6 €/kg could be achieved with a hydrogen consumption of 210 kg/d, which corresponds to current costs of 7.65 €/kg. Therefore, I expect sites with a current cost of 7.65 €/kg or below to become profitable in the near future (dashed lines in Figure 17).

When assuming a pipeline length and transmission cable length of 7000 m, both with six intersections, i.e. the least favorable position, a hydrogen consumption of 1660 kg/d would be necessary to achieve hydrogen costs of 7.65 €/kg.

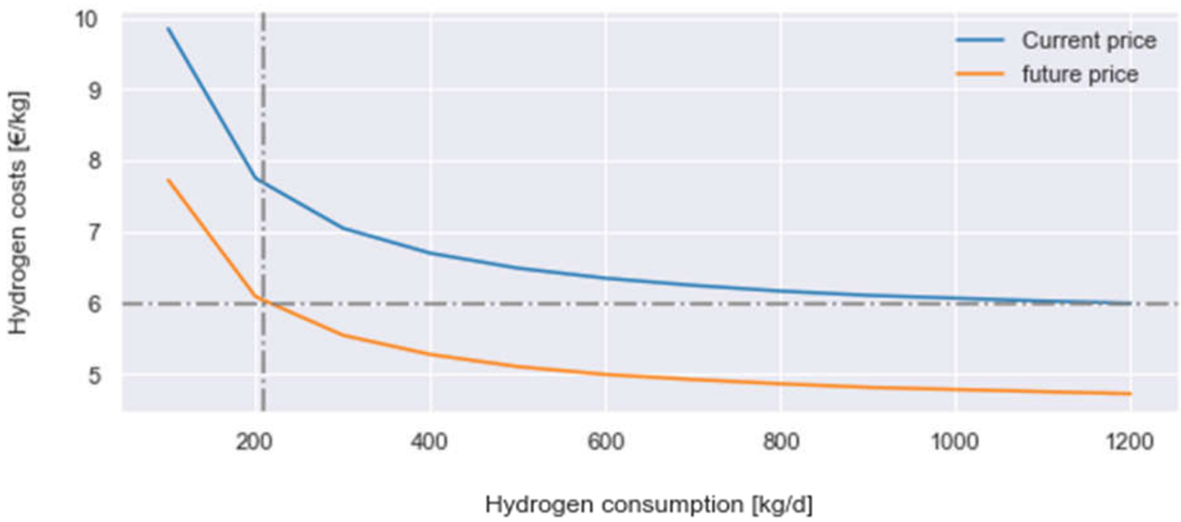

Figure 17: Costs for hydrogen production with current parameter costs and price reduction (capex stack rate reduction = 50 %, capex electrolysis system reduction = 25 %, PEM stack efficiency increase = 25 %; pipeline 500 m; no intersections, 500 m transmission cable, no intersections).

The costs model was applied on overall 9965 potential sites for electrolysis, equal to an area of 623 km². This area increases to 1143 km² when the whole standing windmill stock is considered. The cost model applied on these sites show, that the lowest costs for hydrogen provision achievable is 6.35 €/kg for windmills outside WEG (respective 6.34 €/kg considering the complete stock). Figure 18 shows the areas with their corresponding production costs.

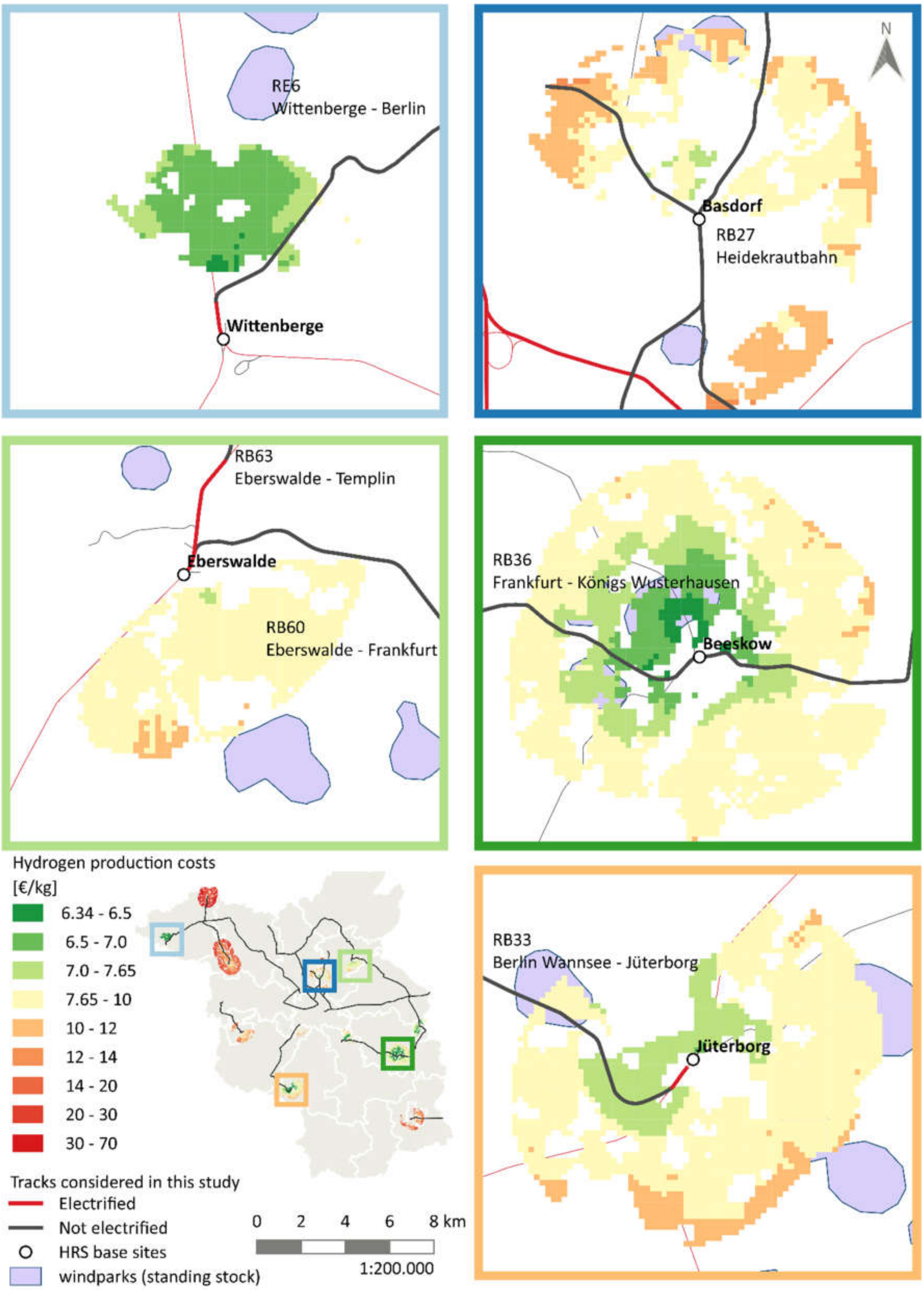

Figure 18: Site-specific hydrogen production costs.

Assuming that current production costs of 7.65 €/kg and below could become cost competitive in the near future (see above), two railway lines (RB33, RB36) could be operated under competitive conditions until 2030. At these connections (see Table 11) - which tackle up to 1.93 million train-km/a - potentially 1073 thousand liters of diesel could be saved each year. This corresponds to a potential hydrogen consumption of 367 tons/a. If the entire standing windmill stock is considered, this increases to six lines (RE6, RB27, RB33, RB36, RB60, RB63) with annually 6.27 million train-km potentially 4081 thousand liters of diesel (resp. 926 tons of hydrogen).

Table 11: Railway lines with hydrogen production costs below 7.65 €/kg, for windmills outside WEG (RB33 and RB36) and for the complete windmill stock (all rows).

HRS	Railway line	Mill. train-km/a	Diesel consumption [t/a]	Hydrogen consumption [t/a]
Basdorf	RB27 Heidekrautbahn	0.94	780	183.8
Jüterborg	RB33 Wannsee – Jüterborg	0.80	508	156
Eberswalde	RB63 Eberswalde – Templin	0.36	125	70
Frankfurt/ Eberswalde	RB60 Frankfurt - Eberswalde	0.70	246	137.5
Beeskow	RB36 Frankfurt – Königs Wusterhausen	1.13	393	220.4
Wittenberge	RE6 Gesundbrunnen– Wittenberge	2.34	1376	457.8

3.3.2 Sensitivity analysis

In this section the results for the sensitivity analysis are shown for several parameters. Each parameter is exemplarily shown for two hydrogen consumption levels (500 kg/d and 1000 kg/d) with an assumption of a 3-kilometer pipeline and a 3-kilometer transmission cable, both with three intersections. Figure 19 shows the diagrams for the sensitivity analysis for the summed capex and opex and the windmill opex. The diagram shows, that both overall capex and overall opex have a linear influence on the hydrogen costs. The overall capex has a stronger effect on the hydrogen costs, because opex is calculated as an annual percentage of capex, meaning a decrease in capex leads to a decrease in opex, too.

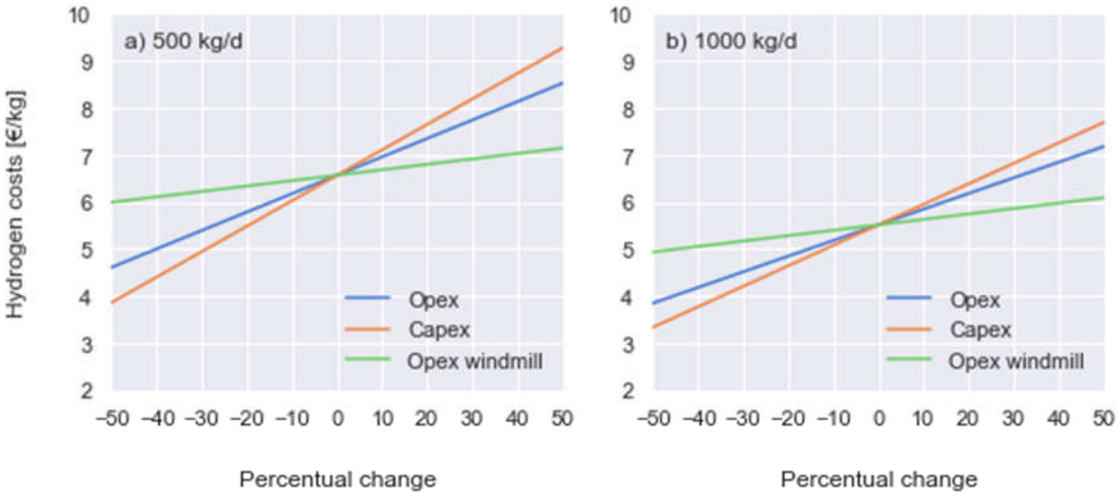

Figure 19: Sensitivity diagrams for overall capex and opex.

The BWE predicts, that wind power electricity prices between 0.0285 and 0.036 €/kWh are necessary to make the operation of aged windmills profitable. In the cost model I assumed 0.0285 €/kWh as the opex for wind power. This might vary by location, turbine type and by the individual condition of a windmill. With an electricity price increase of 50 % the hydrogen costs increases from 7.94 €/kg to 8.71 €/kg (Figure 19a) respectively from 6.80 €/kg to 7.57 €/kg (Figure 19b).

Figure 20 shows the influence of the electrolysis parameters. By reducing the stack costs by 50 %, hydrogen costs of 7.94 €/kg decrease to 7.30 €/kg (Figure 20a). If the efficiency of the electrolysis is increased by 50 % the hydrogen costs drops to 6.53 €/kg. For a consumption of 1000 kg/d (Figure 20b) the costs drop from 6,80 €/kg to 6.15 €/kg with decreasing stack costs and to 5.38 €/kg with increasing electrolysis efficiency. The strong stack cost sensitivity shows that a price decrease for PEM stacks could enhance profitability considerably.

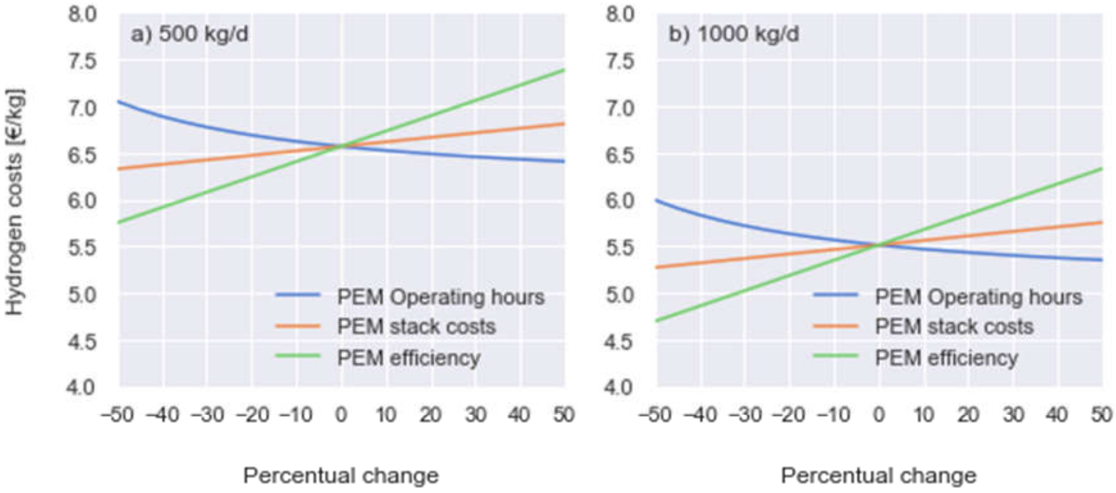

Figure 20: Sensitivity diagrams for electrolysis cost parameters.

Unlike other parameters, the influence of the annual operating hours of the electrolyzers on the hydrogen costs is not linear. The annual workload has a strong effect when it decreases and a weaker effect when it increases. This shows, that an economic operation of an electrolyzer is strongly related to its utilization. The higher the annual workload, the lower are the costs per kilogram hydrogen. This effect weakens when the workload converges upon the maximum workload of 8760 hours. The relationship between the annual workload and the resulting hydrogen costs is discussed in the recent literature[11,43].

4 DISCUSSION

4.1 Main findings

The results of this study suggest, that a FCEMU operation with hydrogen produced from local wind power is generally feasible in Berlin/Brandenburg. With the DMU-bound rail operation in the study region, an annual demand of 1982 tons hydrogen could be generated. The installed wind power capacity could provide sufficient energy to produce the potential demand.

At favorable sites, a hydrogen demand of 1600 kg/d is necessary to make the costs of hydrogen production competitive. Due to future decreases in electrolysis costs and increases in electrolysis efficiency the needed consumption is likely to decline (210 kg/d at favorable sites, 1660 kg/d at the least favorable sites).

The main factor determining unit hydrogen production costs is the potential hydrogen consumption volume. Other factors determining the costs of production are the distances between the wind park, the place of electrolysis and the place of withdrawal (HRS) as well as the landscape type in which pipelines and electric transmission cables need to be installed.

In Brandenburg, the lowest costs for hydrogen production are estimated around 6.34 €/kg which slightly exceeds the threshold for competitive costs of 6 €/kg. Assuming a decrease in PEM stack and system costs as well as an increase in efficiency for electrolyzers, onsite hydrogen from local wind power is likely to become cost-competitive in the near future.

4.2 Limitations

Generally, the study region seems to bear great potential for the coupling of wind-energy and train operation given a great number of potential railway kilometers and the available wind power capacity as shown in sections 3.1.1 and 3.2.1. However, there are some limitations to be considered which will be discussed in the following sections.

4.2.1 Assessment of potential hydrogen consumption

In general, I considered most DMU-operated train lines in Brandenburg suited for the study. However, in practice many lines could be operated with battery electric multiple units (BEMU), too. Various technical factors play a role, but often it is a political decision which technological solution will be applied.

The potential hydrogen consumption is calculated with a fix value of 0.23 kg/km, which is approved by recent research[42,43,54]. This mostly varies due to seasonality but can also vary due to route characteristics and varying design requirements. The complexity of a more detailed assessment of the route specific hydrogen costs is beyond the scope of this work but is worthwhile considering.

The localization of the HRSs is strongly based on insight of the local railway system, and therefore requires knowledge of the requirements of the regional transport system in order to transfer the approach to other regions or means of transport.

I determined HRS base sites with the underlying condition, that their position does not require changes in the current railway operation and timetables. If one considers the locations of current diesel refueling stations, it becomes clear, that they are often located where refueling requires additional service trips (which come with additional costs). Such locations could be considered in the HRS-base layer, too. More liberal assumptions in assigning HRS base sites could reduce the hydrogen production costs significantly but also come with the possibility of HRS-sites being set at locations inappropriate for passenger rail service. Due to this trade-off this should rather be evaluated for individual plants than on an overall regional analysis.

4.2.2 Assessment of suitable rail-adjacent wind power

It might seem arbitrary to exclusively consider wind power as renewable energy source. Partly, the motivation of this work is to assess, if alternative marketing schemes for aged

windmills becoming ineligible to receive EEG-compensation could be found. In future works, it would be worthwhile to consider additional renewable energies (e.g. photovoltaic panels).
Windmills and wind parks considered in this study vary in location (average wind speed), hub height and turbine type. Whether after 20 years of plant operation, a further operation is feasible, is mainly a question of the turbine type. Some models are very robust while some models might develop irreparable damages after years of operation. A technological evaluation, which models qualify for long-term operation is beyond the scope of this work.
For the wind park affiliation, the threshold of 0.7 is determined empirically and only validated by the size and distribution of the resulting wind parks. Whether the assumption of minimal four windmills per wind park is adequate or not, could be evaluated in future works.
The wind-power sufficiency analysis is performed with model data from renewables.ninja[58] which are based on MERRA2- reanalysis data[59], meaning that the hourly production input for each windmill is not based on ground-truth data. Since measured outputs on plant scale were not available for varying locations and turbine types, the usage of the peer-reviewed and accuracy- tested model data provided a comparable and reproducible outcome.
The necessary rated capacity - derived from several wind park's PDC - is defined to provide sufficient energy at all times for all regions and turbines in Brandenburg. This was done because high reliability and low default rates are especially important in railway operation. A problem arising from this value is, that often wind parks are oversized and the level simulations show, that the hydrogen storages are often full. The resulting exceed energy or exceed hydrogen is not considered in this analysis. Possible marketing schemes should be considered in future works. However, for the purpose of regional analysis, this threshold provides a good estimate for the necessary capacity to ensure hydrogen provision. On a case-by-case level, the necessary rated capacity could be chosen more individually.

4.2.3 Evaluation of suitable sites for on-site electrolysis

The buffer size of seven kilometer to evaluate the maximum distance between electrolysis site and wind park/HRS is derived from a projected real-world project which is not yet published (see section 2.5.1). Longer length for pipelines might be fundable, but the longer the pipeline will be, the more timely, costly and legally exhausting will be the approval procedure. The same accounts for the electrolysis sites. If the facility is located on a different site than the fueling station, additional legal approval schemes apply. Each legal admission comes with costly and timely procedures such as environmental impact assessments and technical approval assessments. These – besides the investment costs- can question the general feasibility of a project. Since the feasibility of such a project varies with the individual stakeholders involved, this effect could not be considered in this study.

Due to the scope of this work, the constraints used in this study are nature conservation areas, residential areas and waterbodies. This choice is only a proportion of areas not suitable for electrolysis facilities. In future works, other land uses and especially property rights should be taken into account.

The hydrogen costs calculated in this study compare to other published costs. The literature proposing hydrogen production costs consider mostly individual road traffic[37] or general traffic on a regional to national scale[11,42]. However the estimated costs of e.g. 5,12€/kg[37], 5.99 €/kg[42] and even 10 €/kg[11] found in the literature are comparable with the results of the cost model developed in this work. With an assumed consumption of 1600 kg/d[37] the model developed in this work computes hydrogen production costs between 5.91 €/kg and 7.73 €/kg. Considering a lower hydrogen production of e.g. 600 kg/d costs between 6.35 €/kg and 11.19 €/kg are estimated, which can be still considered as in the range of the above-mentioned published costs.

As discussed in 4.2.2 it is expected, that exceed hydrogen or energy might be produced which could generate additional income and reduce the costs significantly. Production costs could additionally be lowered through an increased hydrogen consumption, which could be achieved by selling hydrogen to industrial consumers, feeding into the natural gas grid or by making the hydrogen available to other means of (public) transport such as bus services, municipal waste collection, ferries or to individual road traffic. Quantifying these possible benefits however is not within the scope of this study and could be carried out in future works. An additional marketing model could give insight on the cost-effect of exceed energy in future works.

The pipeline costs and transmission line costs depend on the landscape. As a proxy for the landscape type I used the number of streets and waterways the pipelines and transmission lines intersect. Land uses (forestry, agriculture, etc.) could not be considered within the scope of this work but would yield far more detailed costs.

I assessed the cost of hydrogen production in this work. The costs for implementing FCEMU trains (e.g. investment costs for vehicles, adjustments in maintenance equipment and machinery, training expenses for maintenance staff and drivers) could not be considered due to the tight scope of this work and should be considered in future works.

5 CONCLUSION

Interlinking public transport and wind power production as a means of sector-coupling could be a main driver for decarbonizing traffic and help balancing a potential volatile renewable energy system. Public (rail) transport as a stable consumer could function as an early adaptor in hydrogen fueled transport, enabling a better understanding of the technology and pave the way to a functioning and ubiquitous infrastructure for fossil free fuels and a deeply integrated transport-energy system.

This study showed sector-coupling potential on a regional scale and it showed that the potential for integrating energy and traffic via hydrogen is high in Germany, where the public transport is widely powered with diesel, offering chances for large carbon reduction and marketing opportunities for a newly developing technology.

This study was conducted for the railway transport in Berlin/Brandenburg. In future works, the analytical approach could be applied on further regions (federal states) and for other traffic and modes of transport such as public busses, municipal vehicles, waste collection and such.

Although the hydrogen costs for Berlin/Brandenburg calculated in this study are not competitive yet, it should be stated that sector-coupling projects have the opportunity to create strong technological and political pull-effects like prove of feasibility, creation of precedent legal cases and best-practices examples and they also add to scale effects. The network effects of early pilot-schemes play an important role in the early stage of market penetration and can lead to a leverage effect on the market, therefore should not only be judged by simple economic benchmarks.

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7 APPENDICES

Appendix A: Supporting Information

Appendix one gives additional information and background thoughts on the methodology performed in this study. The topics discussed are sequenced according to the thesis structure.

A.1 Approach and Scope

Railway technology options

In this study I assessed exclusively FCEMU-railway operation to substitute the current diesel train fleet in Berlin/Brandenburg. In the past, tracks would have been electrified for this purpose and today most trains in Germany therefor do operate under catenary. However, in the last decades the legal approval procedures necessary to electrify tracks progressively became more costly and time consuming. Today this procedure requires several stages of public planning and can take up to several years. Adapting the vehicle technology to substitute diesel trains rather than electrifying tracks can be a more practicable way to reduce carbon emissions of the rail transport sector in many cases.

Another reason why exclusively FCEMU-operation was considered is the possibility of hydrogen being a key factor in the transformation to a renewable energy system. In the climate action plan 2050[75] Germany aims to cut extensively greenhouse gas emissions by 2050. With a carbon neutral energy system, problems related to the volatile nature of renewable energies will arise. Enabling deeper sector coupling and seasonal energy storage, hydrogen can play a key role in the future of the energy and transport sectors.

Finally, this study assessed FCEMU-operation as means of alternative use cases for aged windmills ineligible to receive EEG-compensation. Due to the volatility of wind power, it would not be feasible to load BEMUs with local windmills. Only the possibility of storing hydrogen (and therefore considering FCEMU) makes this scenario feasible.

Railway line and railway networks

Throughout this work I used the terms railway network and railway line. A railway network is usually a group of railway connections for which the transport contract is jointly tendered (e.g. Stadtbahn II) and therefore contracted by the same (local) transport agency (e.g.

Ostdeutsche Eisenbahn GmbH – ODEG). The railway networks considered in this study are shown in Table 9. A railway line (e.g. RB33 between Berlin Wannsee and Jüterborg) is operated within a railway network. It is running on a route, connecting a start- and end point (train stations). Often, additional trips are taken into consideration to cope with high utilizations during the busiest hours ('Verstärkungsfahrt'). One exception from this terminology is RB27 ('Heidekrautbahn') which is considered as a railway line even though is is running on different routes.

FCEMU-suited railway-lines

The criteria on how a railway line was categorized as suitable or not-suitable for FCEMU-operation has been explained in 2.3.1. The specific reasons for the railway lines excluded from the study are explained in more detail below.

The main track on the line RB34 (Stendal – Rathenow) has already been electrified. The side-track on which the diesel trains are operated has not been electrified. It can be expected, that the legal approval procedures necessary for a future electrification of the side-track is likely to experience low barriers, making electrification a better option. Another viable option would be to use BEMU on this line, since start- and end stations are both electrified.

RB 35 (Bad Saarow – Fürstenwalde(Spree)) has only a length of 13 km and starts/ends at an electrified station (Fürstenwalde) which makes it well suited for BEMU operation. With its short length, the line would not be able to generate hydrogen consumptions high enough to make investments in infrastructure or production facilities profitable. The same applies for RB 25 (Ostkreuz - Werneuchen) with a length of 26.6 km of which 16.3 km are already electrified (from Ostkreuz till Blumberg-Rehhahn). A hybrid BEMU could recharge while driving under catenary.

The railway line RB66 (Berlin Gesundbrunnen – Stettin) is widely electrified with further electrification in plan. Electrification is also planned for RB 61 (Angermünde - Schwedt(Oder)).

The railway line RB65 (Cottbus - Zittau) was not considered, because the main part of the line is not within the study region.

A variety of factors influence which technology is the most reasonable for a specific region or railway line, as can be seen in the examples above. In practice, however, political reasons are often the main driver for decisions favoring certain technologies.

Hydrogen consumption

The potentially generated hydrogen consumption when using FCEMU is derived from the only passenger FCEMU-model available on the market, the Coradia iLint from manufacturer Alstom. The hydrogen consumption of the iLint ranges between 0.18 kg/km and 0.25 kg/km depending on requirements of the served route[43,54]. Since the assessment of these route-requirements did not fit into the scope of this work, I assumed a fixed value of 0.23 kg/km.
The iLint is a 2-car train. Some DMUs used in Brandenburg are 3-car trains (compare Table 2). Applied on the iLint, this could mean higher consumption per kilometer or a higher circulation. A 3-car passenger FCEMU is currently not available on the market, so this discrepancy could not be considered in this study.

HRS-sites

The HRS-sites where determined by the criteria defined in 2.3.2. Because timetables and circulation plans ('Umlaufpläne') are often the result of longstanding developments and because railway lines are part of a complex traffic system, where altering circulations is associated with additional efforts and likely with additional expenses, I chose only HRSs, for which such alterations wouldn`t be necessary.

A2 Assessment of suitable rail-adjacent wind power

Degradation and turbine robustness

To determine if a continued operation of aged windmills is feasible, I performed a literature research on turbine robustness and on degradation of windmill performance. As of individual turbines, the performance decline over time is negligible, but general turbine deaths can be expected for aged windmills[76]. Recent publications suggest that some turbine types might be more durable than others[15,76], however, to my knowledge there is no scientific work evaluating lifespans of turbines currently in service, and therefore, I could not include windmill degradation into this study.

Wind park Affiliation

The wind park affiliation was performed using the kernel density tool of ArcGIS 10.2.1. A guide to the tool can be found under (https://pro.arcgis.com/de/pro-app/tool-reference/spatial-analyst/how-kernel-density-works.htm, accessed 09.10.2019). I performed the analysis with the parameter set shown in Table 12.

Table 12: Kernel Density tool- parameters

Parameter	Value	Unit
Cell size	100	m
Range	1500	m
Type	unweighted	

I derived the threshold of 0.7 with the assumption that a wind park consists of several windmills while the border of the wind park should be as close around the windmills as possible. I tested kernel densities for several parameter sets. Figure 21 shows kernel density estimates for varying parameter sets. Each parameter set comes with certain trade-offs (too strong influence of high-capacity windmills, under consideration of small plants, integration of windmills far away from the center of the wind parks, wind parks consisting of one windmill only). With the given parameter set in table x and a threshold of 0.7, I found a tolerable balance between the occurring tradeoffs.

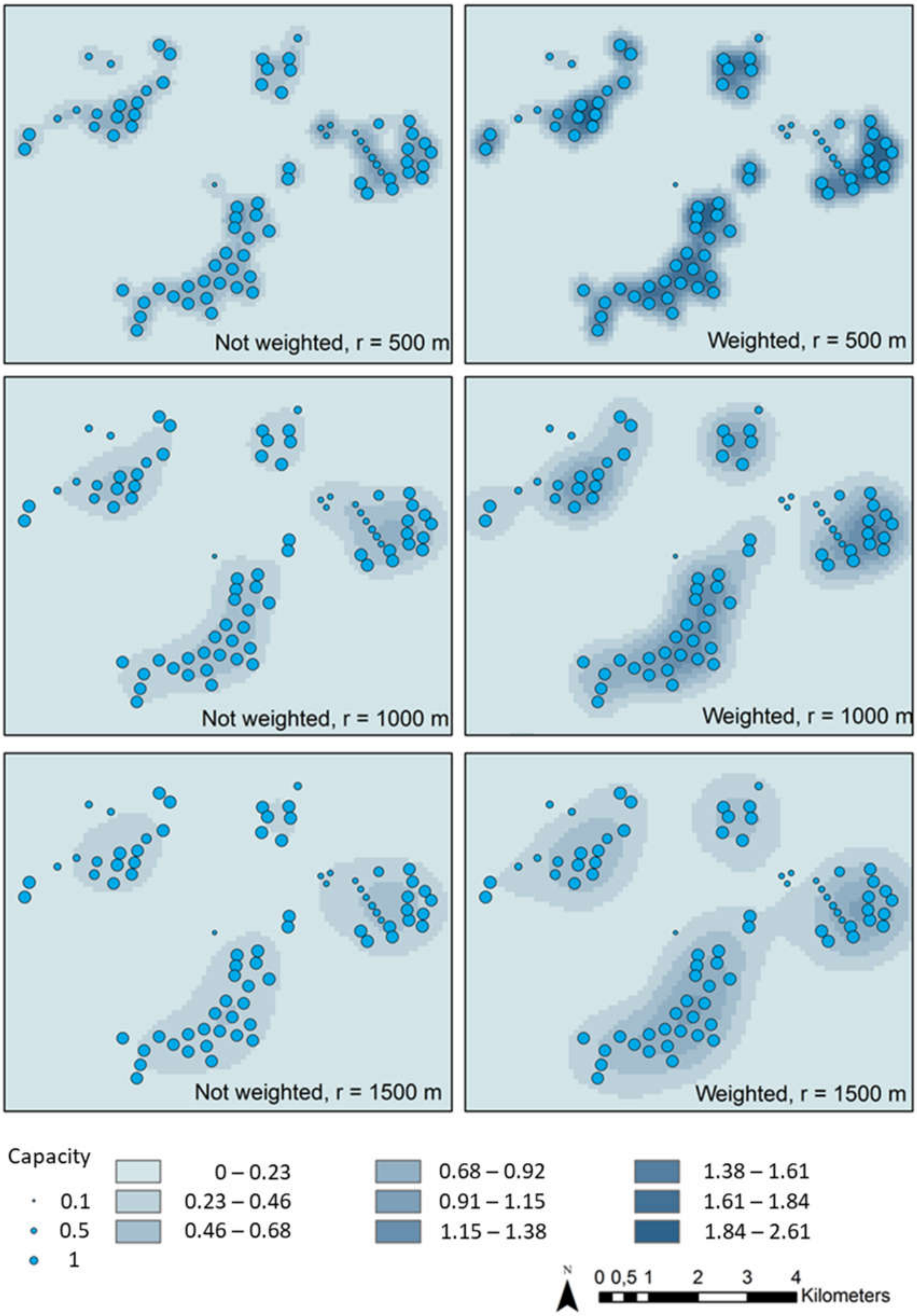

Figure 21: Kernel density raster for varying parameter sets.

Wind power production sufficiency analysis

The wind power production sufficiency analysis is separately discussed in Appendix B.

A3 Evaluation of suitable sites for on-site electrolysis

On-site space requirement

The cell size of 250 meter used in the geoprocessing is chosen to account for the space requirements for on-site electrolysis and storage. HRSs for railway require around 4000 m² area[43]. With 62500 m² per electrolysis-site, I assumed to meet the required area with additional space (for electrolysis, storage, etc.) multiple times.

PEM stack parameters.

The range of PEM lifetimes reported in the literature consulted for this study varies widely between 7.4 and 20 years[27,64,65]. Other authors name operating hours between 60.000 to 100.000 hours[12]. Assuming annual operation of 3500 hours (as used in this study), this would result in a lifespan of 17.1 – 28.6 years. Assuming 8000 hours of operation would result in a lifespan of 7.5 t- 12.5 years. Since the most recent studies varied between lifespans of 7.5 and 20 years, I decided to assume a lifespan of 15 years as a cautious compromise.

Several studies suggest a degradation of PEM stacks over time, with annual degradation rates between 1 % and 4 % of the stack efficiency (at 8000 hours of operation annual). Due to degradation, PEM stacks are required to be exchanged after a certain time period (stack lifespan). The electrolysis systems costs refer to the plants auxiliary machinery (heat exchanger, pumps, gas separators, etc.) and the buildings, which usually have longer lifespans. To account for the stack degradation and the varying lifespans I assumed different costs and lifespans for stacks and the rest of the electrolysis system.

The minimum load of PEM stacks is reported to be 5 %[10]. This was not considered in the cost model because I assumed fix operational hours for electrolysis. The minimum PEM load was also not considered in the level simulation for hydrogen storages (compare 2.4.3 and appendix B) because of the low minimum load and because the level simulation was performed utilizing the daily aggregated wind output.

Profitability

I assumed 0.0285 €/kWh as the wind opex. The cited reference describes several scenarios for continued operation of aged windmills, where windmills are maintained on different levels. In the scenario leading to a necessary income of 0.0285 €/kWh, the maintenance level is rather low and windmills are more likely to fail. The study assumes a 0.75 €/kWh return at a market price of 0.0285 €/kWh. The study suggests, that to avoid major damages or to replace costly parts, higher incomes (up to 0.036 €/kWh) would be necessary. It should be assessed in future works, if additional income could be generated from marketing excess hydrogen to subsidize these expenditures.

Funding:

I assumed a general capex funding of 45 % according to the General Block Exemption Regulation (GBER) by the European commission[72]. However, for certain modules national or stately government funding could provide higher funding rates. For example, corresponding to regulation (EC) No 1370/2007 of the European parliament[73] (public passenger transport being an essential service), funding rates of up to 100 % of the investment costs (e.g. for HRSs) are possible. In the feasibility study for FCEMU operation in Thüringen, the authors suggest an 80 % investment funding rate as a typical maximal public funding rate in Germany. Additionally, opex funding by stately funding schemes are possible, yet the concrete possibilities and whether European, national and stately funding schemes could be combined, is not inside the scope of this work.

Additional project costs

The additional project costs account for costs associated with land rent, legal expenditures and expenditures due to tender processes. Project costs are implemented in the module specific capex and opex. In Germany, costs for planning and legal approval can make up a relevant part of the overall costs. The actual share of those expenditures varies strongly with the specific dimension of the plant and the location and cannot be assessed properly within this work.

Infrastructure density

The capex for pipelines and electric transmission cables are dependent on various land-use factors. A pipeline constructed on open field will produce different costs than a pipeline laid through a forest. Due to its complexity, the consideration of land-use types was outside the scope of this work. Instead, I used the intersections with streets and waterways as a proxy, giving the assumptions that each road and river crossing brings additional costs for both pipelines and electric transmission cables. The costs for pipelines and electric transmission cables are calculated as described in equation (13).

The distances calculated between wind parks and HRSs are the shortest linear routes. In practice, it is unlikely that pipelines and transmission cables would be laid along these direct routes. To compensate for this, I added a detour factor of 1.2 to the route distances. It would be worthwhile to empirically assess more sophisticated detour factors in future works.

A4 Further issues

Seasonality

Seasonality occurs in various ways: timetables can vary through the week (weekday and weekend) and seasons (summer and winter timetables), the hydrogen consumption of the FCEMU is sensitive to temperature and wind speeds which vary by season as well. The circulation derived from the timetables (and in that manner the hydrogen consumption) is averaged over week and year.

Since implementing seasonality into the tight scope of this work was not possible, I have chosen the hydrogen consumption for the iLint rather pessimistic (0.23 in a range from 0.18 – 0.25[43] with the topology in Brandenburg being rather unambitious in energetic terms) so that the hydrogen consumption is rather overestimated. The minimal rated wind power capacity of 24 kW/kg leads to an overproduction rather than to shortages as well. Both assumptions making up for possible seasonal deviations.

Operating structures and ownership

Usually transport contracts are tendered not for single railway lines but for railway networks (e.g. Ostbrandenburg, Nordwestbrandenburg, Stadtbahn II etc.). In this approach, each railway line was evaluated for annual train-km, diesel consumption and hydrogen consumption. This brings the advantage of being able to identify points, where several train lines meet, independent from existing operating structures. At those points, an HRS could provide several lines simultaneously enabling larger daily hydrogen consumptions. This could also be interpreted as valuable information for designing upcoming transport tenders. However, this comes with two main issues:

1. Train-fleets are usually operated on whole railway networks. Individual trains can be operated on varying railway lines in the networks or even in different networks. Nevertheless, the vehicles could use the same infrastructure for fueling and maintenance.
2. In tender documents the vehicle technology is often predetermined. Switching technology at individual train lines might be difficult regarding existing traffic contracts.

A similar problem arises considering the operating structures of windmills. Often windmills are part of a wind park, operated by a certain company. Those wind parks were erected prior to the assignment of WEGs in Brandenburg. If one considers only windmills outside WEGs, windmills are considered as single plants or small group of plants when in practice, they are part of larger wind parks.

This occurs especially at the outer edge of the WEGs when windmills are directly outside the assigned WEGs. However, when considering all windmills in Brandenburg, many of those will be inside WEG`s at locations with high wind speeds, making a repowering a profitable option. To consider both cases, I conducted the analysis for both options.

APPENDIX B: PERCENTAGE DOLDRUMS COVERAGE

The PDC was derived from simulating the hydrogen storage levels for varying daily consumption loads and wind parks with varying characteristics. In order to conduct the simulation, I first selected wind parks which vary in their rated capacity, in their average turbine capacity, in turbine age, in number of turbines and in the specific location from the wind park data set derived from the windmills outside WEG (Table 13).

Table 13: Affiliated wind parks used to determine the minimum necessary rated capacity.

Wind park	Capacity	Mean Capacity	Number windmills	Main turbine type
Jüterborg	5	1.67	3	Enercon E66
Schwarzheide	6	2.00	3	Vestas V80
Kloster Lenin	7	1.75	4	GE 1.5 SL Vestas V90
Bad Liebenwerda	8	2.00	4	Vestas V90
Kloster Lenin	10	2.00	5	Vestas V90
Luebbenau	10	2.00	5	Vestas V90
Frankfurt (Oder)	11		7	Enercon E40 Vestas V90
Glienicke	15	1.50	10	RE Power MD77
Wriezen	15	1.60	7	Vestas V44 Vestas V80 Vestas V112
Jüterborg	18	1.50	12	Enercon E40 Enercon E70
Zitz	20	1.00	20	Micon NM64c
Seelow	30	1,76	17	Enercon E66 Enercon E82 Vestas V90

For each wind park, I selected the according individual windmills and parsed the hourly energy production for each windmill from the renewables.ninja data server (see appendix C).

The renenwables.ninja data model provides the hourly energy output for an individual windmill when given its location, hub height, turbine capacity and turbine type. I grouped the hourly time series of the produced energy for each wind park. Since I consider 3-day to 10-day storages I aggregated the hourly output on daily output and run the storage simulation as described in 2.4.3 (for daily hydrogen consumptions of 250 – 1500 kg/d in steps of 50 and 3-day, 5-day, 7-day and 10-day storages). For each simulation run, I calculated the PDC and recorded when a PDC of 100 % was achieved (see Table 14 for a subset of the considered wind parks). I derived the minimum necessary rated capacity per kilogram hydrogen, by dividing the daily hydrogen consumption with the lowest possible rated wind park capacity to achieve a PDC of 100 % at all times throughout the reference years.

Table 14: PDCs of affiliated wind parks for varying hydrogen consumptions (on two pages).

Windpark		250	300	350	400	450	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
Schwarzh.	3	100																									
	5	100	100																								
	7	100	100																								
	10	100	100	100																							
Kloster Lenin	3	100	100	100	100																						
	5	100	100	100	100	100																					
	7	100	100	100	100	100	100																				
	10	100	100	100	100	100	100	100																			
B.Liebenw.	3	100	100	100	100	100																					
	5	100	100	100	100	100	100	100																			
	7	100	100	100	100	100	100	100	100																		
	10	100	100	100	100	100	100	100	100	100																	
Kloster Lenin	3	100	100	100	100	100	100	100	100																		
	5	100	100	100	100	100	100	100	100	100	100																
	7	100	100	100	100	100	100	100	100	100	100	100	100														
	10	100	100	100	100	100	100	100	100	100	100	100	100	100													
Lübbenau	3	100	100	100	100	100	100	100	100	100																	
	5	100	100	100	100	100	100	100	100	100	100	100															
	7	100	100	100	100	100	100	100	100	100	100	100	100	100													
	10	100	100	100	100	100	100	100	100	100	100	100	100	100	100												
Frankfurt	3	100	100	100	100	100	100	100	100	100	100																
	5	100	100	100	100	100	100	100	100	100	100	100	100	100													
	7	100	100	100	100	100	100	100	100	100	100	100	100	100	100												
	10	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100											
Glienicke	3	100	100	100	100	100	100	100	100	100	100	100															
	5	100	100	100	100	100	100	100	100	100	100	100	100	100	100												
	7	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100											
	10	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100										
Wriezen	3	100	100	100	100	100	100	100	100	100	100																
	5	100	100	100	100	100	100	100	100	100	100	100	100	100													
	7	100	100	100	100	100	100	100	100	100	100	100	100	100	100												
	10	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100											
Zitz	3	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100									
	5	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100						
	7	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100			
	10	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	
Seelow	3	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
	5	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
	7	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
	10	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

Table 15 shows the minimum rated capacity per wind park and per kilogram hydrogen. Assuming that a larger hydrogen storage could compensate for longer doldrums and therefore reduce the necessary wind park capacity I tested it for several storage sizes and compared the average rated capacity for each size (see Table 15). The maximal necessary rated capacity is 24 kW/kg. With this value it is likely, that no shortages in hydrogen provision will occur.

Table 15: Subset of necessary rated capacities for selected wind parks.

		250	**500**	**750**	**1000**	**1250**	**1500**
Min. possible wind park capacity [kW]							
	3-day	6000	10000	15000	20000	29800	29800
	5-day	6000	8000	10000	20000	29800	29800
	7-day	6000	7000	10000	20000	20000	29800
	10-day	6000	7000	10000	15000	20000	29800
Min. possible wind park capacity [kW/kg]							
	3-day	24,0	20,0	20,0	20,0	23,8	19,9
	5-day	24,0	16,0	13,3	20,0	23,8	19,9
	7-day	24,0	14,0	13,3	20,0	16,0	19,9
	10-day	24,0	14,0	13,3	15,0	16,0	19,9
Derived min. rated capacity threshold							
	24 kW/kg	6000	12000	18000	24000	30000	36000

APPENDIX C: DATA AND SOFTWARE

The data used in this study is described in this section.

All geographical data was processed in the geodetic coordinate reference system ETRS89, Datum European Terrestrial Reference System 1989, Ellipsoid GRS 1980, prime meridian Greenwich, UTM zone 32N with the EPSG Number 25832. This reference system is used by the German Federal Agency for Cartography and Geodesy. Each layer was clipped to the extent of Berlin and Brandenburg.

The processing was mainly done using Python 3.6.6., ArcGIS 10.2.1 and Quantum GIS 3.0.3. The geoprocessing is scripted and transferable to other regions and/or means of transport.

Residential areas, water bodies and waterways are taken from the Open Street Map project as provided by Geofabrik (accessed at 01.08.2019 from https://download.geofabrik.de/).

The railway lines and the administrative boundaries were taken from the ATKIS data model[77] ('amtliches topographisches kartographisches Informationssystem') provided by the German Federal Agency for Cartography and Geodesy (accessed at 01.08.2019 from https://gdz.bkg.bund.de/).

The nature conservation areas, street network, windmills and wind regions (WEG) were taken from Geoportal Brandenburg, provided by federal State of Brandenburg (accessed at 01.08.209 from https://geoportal.brandenburg.de/startseite/).

The modeled hourly windmill power outputs are taken from https://www.renewables.ninja/[58] based on MERRA2- reanalysis data[59]. The wind power curves are parsed given the turbine type, hub height, power capacity and spatial location.

Appendix D: Declaration of Authenticity

ERKLÄRUNG

Ich erkläre, dass ich die vorliegende Arbeit nicht für andere Prüfungen eingereicht, selbständig und nur unter Verwendung der angegebenen Literatur und Hilfsmittel angefertigt habe. Sämtliche fremde Quellen inklusive Internetquellen, Grafiken, Tabellen und Bilder, die ich unverändert oder abgewandelt wiedergegeben habe, habe ich als solche kenntlich gemacht. Mir ist bekannt, dass Verstöße gegen diese Grundsätze als Täuschungsversuch bzw. Täuschung geahndet werden.

Berlin, den 14.10.2019