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Guido Pleßmann

# **Modeling decarbonization pathways of Europe's electricity supply system until 2050**



Carl von Ossietzky Universität Oldenburg  
Fakultät II – Informatik, Wirtschafts- und Rechtswissenschaften  
Department für Informatik

# **Modeling decarbonization pathways of Europe's electricity supply system until 2050**

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Ossietzky Universität Oldenburg zur Erlangung des Grades und Titels eines

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# Erklärung

Ich erkläre hiermit, dass ich die vorliegende Arbeit selbständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel verwendet habe.

Girona den 27.9.2018,



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Guido Pleßmann



# Zusammenfassung

Der voranschreitende Klimawandel stellt eine der größten Herausforderungen für das Wohlergehen der Menschheit dar. Auf Basis wissenschaftlicher Erkenntnisse, insbesondere durch die des Intergovernmental Panel on Climate Change (IPCC), wurden globale und multinationale Abkommen zur langfristigen Stabilisierung des weltweiten Klimas vereinbart. Das globale Klimaschutzabkommen von Paris im Jahr 2015 zielt auf eine Begrenzung der globalen Erderwärmung von maximal  $2^{\circ}\text{C}$  – bevorzugt höchstens  $1,5^{\circ}\text{C}$  – bis 2100 ab. Um dies zu erreichen hat die EU umfassende Emissionsminderungsziele von -80 % bis -95 % bis zum Jahr 2050 in Energie- und nicht-Energiesektoren vereinbart. Von diesem Ziel leiten sich unterschiedliche Minderungsziele für einzelne Sektoren ab. Für die Erreichung der langfristigen Emissionsminderung werden schrittweise kurzfristigere Ziele für einzelne Mitgliedsstaaten vereinbart. Ein Masterplan für die konkrete Realisierung der sektoralen Emissionsminderungsziele bis zum Jahr 2050 liegt allerdings bisher nicht vor. Dabei wird insbesondere die zweite Hälfte der Umsetzungsphase des Klimaschutzabkommens verschärfte Herausforderungen mit sich bringen. Im Bereich der Energieversorgungssektoren betrifft dies insbesondere den Stromsektor, da dieser mit besonders strengen Minderungszielen belegt ist und zusätzlich eine Verlagerung von Lasten aus anderen Energiesektoren zu erwarten sind.

Eine kostengünstige Umsetzung der Klimaschutzziele im Stromsektor benötigt eine optimierte Planung und Strategie. Langfristige Planungs- und Abschreibungszeiträume für Kraftwerke und ein tiefgreifender technologischer Wandel erzeugen ein komplexes und dynamisches Umfeld. Kurzfristige Entscheidungen haben Auswirkungen auf die mittel- und langfristige Energieversorgungsstruktur. Daher unterstützen modellbasierte Studien zum Umbau der Energieversorgungsinfrastruktur politische Planungsprozesse und geben Einblicke in entscheidungsrelevante technisch-ökonomischer Zusammenhänge. Trotz einer Vielzahl an Studien zur zukünftigen Europäischen Energie- und insbesondere Stromversorgung, besteht zu wenig Kenntnis über den schrittweisen Wandel im Stromversorgungssystem. Dies betrifft insbesondere die Übergangspfade hin zu einem klimafreundlichen System und die technologischen Veränderungen in der Phase ab 2030.

Um diese Lücke zu füllen, skizziert diese Arbeit kostengünstige Dekarbonisierungspfade für



den europäischen Stromsektor zur Erreichung der EU-Treibhausgasminderungsziele. Diese Pfade beschreiben die Umstrukturierung der Energieversorgungsinfrastruktur hinsichtlich Investitionen in Kraftwerks-, Energiespeicher-, und Übertragungsnetzkapazitäten in 5-Jahresschritten bis zum Jahr 2050. Zur Ermittlung dieser Pfade wurde das mehr-perioden, mehr-regionen Energiesystemmodell eesplan-m für den europäischen Stromsektor entwickelt und angewendet. Basierend auf linearer Programmierung ermöglicht es kostenoptimale Investitionsentscheidungen unter Berücksichtigung der technischen und wirtschaftlichen Rahmenbedingungen zu treffen. Dafür wurden Referenzjahre in stündlicher Auflösung berechnet.

Die analysierten Übergangspfade, die zu einer Minderung der Treibhausgasemissionen bis 2050 um -98 % bezogen auf 1990 führen, zeigen, dass erhebliche Investitionen mit der Umstrukturierung der europäischen Stromversorgung verbunden sind. Stromerzeugung aus Photovoltaik (PV) und Windenergieanlagen wird den Großteil der Gesamtstromerzeugung ausmachen. Dazu werden 1.430 GW Windenergieanlagen und 1.260 GW PV-Anlagen im Jahr 2050 benötigt. Um dies zu erreichen, muss ein durchschnittlicher jährlicher Ausbau von ca. 40 GW/a beider Technologien erfolgen. Eine verstärkte internationale Kooperation in der Stromversorgung durch den Ausbau der Grenzüberschreitenden Übertragungsnetzkapazitäten begünstigt die kosteneffiziente Umsetzung der Klimaschutzmaßnahmen im Stromsektor. Energiespeicher in einer Größenordnung von 43 GW Pumpspeicherkraftwerken, 230 GW Batteriespeichern und 260 GW Power-to-gas werden im Jahr 2050 benötigt, um Schwankungen in der Energieversorgung auszugleichen. Die Analyse verschiedener Sensitivitäten verdeutlicht, dass langfrist-Energiespeicher, z.B. Power-to-gas, zur Erreichung von einer Treibhausgasemissionsminderung von -88 % und weniger erforderlich sind. Emissionsintensive Kohleverstromung muss spätestens Mitte der 2030er Jahre beendet werden, um den Dekarbonisierungspfad zu realisieren. Insgesamt ist ein Anstieg der Stromgestehungskosten von rund 60 % zu erwarten. Analyisierte Szenarien weisen diesbezüglich einen Schwankungsbereich von +/- 10 % auf, womit die Kostensteigerung als erwartbar angesehen werden kann. Unter Berücksichtigung externer Kosten zeigt sich ein anderes Bild. Werden steigende Brennstoffkosten, Folgekosten des Klimawandels und weitere externe Kosten berücksichtigt, entsprechen diese nahezu der Steigerung der Stromgestehungskosten des dekarbonisierten Stromsystems.

Aus den Ergebnissen dieser Arbeit lässt sich schlussfolgern, dass ein verlässlicher politischer Rahmen für die erfolgreiche Umsetzung der Klimschutzvorhaben notwendig ist. Ein europaweiter Umsetzungsplan zur Realisierung der Klimaszutzziele im Stromsektor ermöglicht koordinierte Maßnahmen in einzelnen Ländern und kann zu einem insgesamt kostengünstigen Übergang führen. Die Schaffung eines verlässlichen Investitionsumfeldes ist notwendig für Investoren, um einen Anreiz für Investitionen in Kraftwerks- und Speicherprojekte zu

bieten. Ferner muss sichergestellt werden, dass notwendige Technologien, wie z.B. Power-to-gas, und ausreichend Produktionskapazitäten für bspw. Windenergie- und PV-Anlagen verfügbar sind. Sofortiges Handeln ist erforderlich, um Klimaschutz im Rahmen der 2°C Ziele zu realisieren. Investitionen in fossile Kraftwerkstechnologien, die bald nicht mehr wirtschaftlich nutzbar sind, müssen vermieden und auf der anderen Seite Investitionen in erneuerbare Technologien gestärkt werden.



# Abstract

Climate change is one of the most challenging issues faced by humankind today. Scientific evidence regarding the existence of anthropogenic climate change was proven by the Intergovernmental Panel on Climate Change (IPCC). Based on the evidence, negotiations led to international agreements on the long-term stabilization of the climate system. In 2015, a limit on the global average temperature increase was set to 2°C, preferably 1.5°C, until 2100. To achieve this goal on a European scale, the EU agreed to reduce total greenhouse-gas (GHG) emissions by 80 to 95 % by 2050. Thereof, emission targets for individual sectors were derived. The effort is shared among member countries. Individual intermediate targets are being continually negotiated. However, a holistic plan that sets the pathway for implementing effective measures to achieve the GHG emission reduction targets in all sectors by 2050 is missing. It is expected that challenges to achieve the reduction will increase in the last twenty years due to the growing integration of variable renewable energy sources. In addition, anticipated demand shift from other sectors to the electricity sector and relatively strict reduction targets in the latter corroborate the priority to decarbonize the electricity sector.

The cost-effective implementation of measures to achieve the GHG emission reduction targets requires a strategy based on optimal planning. Long-term economic depreciation of power plants and a radical technological change create a dynamic and a complex environment. Decisions taken on short-term scale affect the design of the electricity system on a long term. Therefore, model-based studies help to unveil insights about the transition towards a decarbonized electricity supply and provide important information for planning of the future electricity system. Despite the large number of studies on the future of the electricity sector, cost-effective decarbonization pathways to achieve the GHG emission reduction goals are insufficiently explored. Successive transformation planning of the European electricity system is needed in order to achieve the GHG emission reduction targets by 2050.

This thesis assesses cost-optimal decarbonization pathways for the European electricity sector to meet emission reduction targets by 2050. These pathways outline the transformation of the electricity supply infrastructure in successive 5-years increments until 2050. It includes

investments in power plants, energy storage facilities, and the transmission system. For assessing these pathways, the multi-period, multi-region energy system model *elesplan-m* for European electricity sector was developed and used. This computer model is based on linear programming allowing the assessment of investment decisions constrained by technical and economic circumstances. These decisions are evaluated based on analyzing the electricity supply on an hourly scale for each reference year.

The analyzed decarbonization pathways show that enormous effort is required to cut GHG emissions in the European electricity sector by 98 % by 2050 relative to 1990 levels. According to the investigated pathways, electricity generation by wind and photovoltaic (PV) power will meet the majority of the electricity demand by 2050. This requires 1,430 GW of wind power and 1,260 GW of PV power to be installed by 2050. Therefore, capacity of both technologies needs to be extended by approximately 40 GW on average per year. Enhanced international cooperation through the extension of cross-border transmission capacities allows a cost-effective implementation of climate protection measures in the electricity sector. The proposed electricity system design for 2050 includes 43 GW of pumped-hydro storage, 230 GW of battery energy storage systems, and 260 GW of power-to-gas (PtG) to balance supply and demand mismatches. Several sensitivity scenarios show that PtG is required to achieve climate change mitigation beyond the GHG reduction of 88 %. Carbon-intensive electricity generation technologies, such as coal power, must be abandoned around 2035 to realize effective decarbonization. Cost of electricity supply is very likely to increase by approximately 60 % until 2050. The sensitivity scenarios show the cost increase only deviates by +/- 10 % relative to the reference case. If rising fuel prices, costs due to the impact of climate change, and other external costs would be incorporated in the cost of electricity supply, costs would be comparable to the expected cost increase of deploying renewables.

Based on the results of this thesis, it can be concluded that a reliable political framework is required for a successful implementation of GHG reduction measures in the European electricity supply sector. A European-wide agenda to decarbonize the electricity sector allows cost-effective coordinated actions. A guaranteed reliable environment attracts investors to finance power plants, energy storage systems, and transmission system projects. Furthermore, it must be guaranteed that required technologies, i.e. power-to-gas, and manufacturing capacities for PV and wind power, are available. Immediate action is needed to realize climate change mitigation within the 2°C limits. Among other requirements, investments in coal power must be avoided and replaced by investments in renewable energy.

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# Contents

Zusammenfassung

Abstract

Acknowledgements

Acronyms

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Motivation and research objective . . . . .	1
1.2	Approach and scope . . . . .	10
1.3	Structure . . . . .	13
<b>2</b>	<b>Background on electricity supply</b>	<b>15</b>
2.1	Electricity system technologies . . . . .	15
2.1.1	Power generation . . . . .	15
2.1.2	Energy storage systems . . . . .	19
2.1.3	Transmission and distribution system . . . . .	24
2.2	Electricity supply in Europe . . . . .	25
2.2.1	Electricity demand and supply . . . . .	26
2.2.2	Power generation and transmission capacity . . . . .	30
2.2.3	Greenhouse gas emissions . . . . .	31
2.2.4	European climate policy . . . . .	33
2.3	Electricity supply system planning . . . . .	36
2.3.1	Classification of energy system modeling tools . . . . .	36
2.3.2	Challenges and key aspects of energy system modeling . . . . .	41
<b>3</b>	<b>Modeling of the electricity supply system</b>	<b>49</b>
3.1	Evaluation of available models . . . . .	49
3.1.1	Model requirements . . . . .	49
3.1.2	Discussion of suitability . . . . .	52
3.2	Considered technologies . . . . .	58



## Contents

3.3	Study region . . . . .	60
3.4	Theoretical framework of <i>elesplan-m</i> . . . . .	61
3.5	Model structure and notation . . . . .	68
3.5.1	Objective function . . . . .	68
3.5.2	Electricity generation . . . . .	70
3.5.2.1	Renewable energy sources technologies . . . . .	70
3.5.2.2	Conventional power plants . . . . .	71
3.5.3	Energy storage systems . . . . .	72
3.5.3.1	Battery and pumped-hydro storage systems . . . . .	72
3.5.3.2	Power-to-Gas . . . . .	75
3.5.4	Transmission system . . . . .	77
3.5.5	Demand coverage and dispatch . . . . .	78
3.5.6	Domestic supply rate . . . . .	79
3.5.7	GHG emission constraint . . . . .	79
3.6	Software implementation and solver . . . . .	80
<b>4</b>	<b>Base scenario and model parameters</b> . . . . .	<b>83</b>
4.1	Fundamental economic parameters . . . . .	84
4.1.1	Weighted average cost of capital . . . . .	84
4.1.2	Cost data reference year . . . . .	85
4.2	Power generation technologies . . . . .	86
4.3	Fuels . . . . .	88
4.4	Energy storage systems . . . . .	89
4.4.1	Batteries and pumped-hydro . . . . .	89
4.4.2	Power-to-gas . . . . .	90
4.4.3	Gas storages . . . . .	93
4.5	Transmission system . . . . .	94
4.6	GHG emissions of power generation . . . . .	94
4.7	GHG emission constraints . . . . .	95
4.8	Electricity demand . . . . .	96
4.9	Renewable energy sources based supply . . . . .	97
4.10	Power plant and transmission capacity . . . . .	99
4.10.1	Power plants . . . . .	100
4.10.2	Transmission system . . . . .	101
4.11	Scenario definition . . . . .	101
4.11.1	Sensitivity on economics . . . . .	102
4.11.2	Technical and political boundary conditions . . . . .	104
4.11.3	Snapshot planning . . . . .	105

<b>5</b>	<b>Results – A decarbonization pathway towards 2050</b>	<b>107</b>
5.1	Power generation and capacity . . . . .	109
5.2	Energy storage systems . . . . .	113
5.3	Spatiality, transmission capacity and power exchange . . . . .	114
5.4	Excess electricity and losses . . . . .	119
5.5	Cost and investment needs . . . . .	121
<b>6</b>	<b>Results – Alternative pathways</b>	<b>125</b>
6.1	Overview on scenario results . . . . .	125
6.2	Generation mix . . . . .	126
6.3	Energy storage systems . . . . .	129
6.4	Regional distribution and transmission . . . . .	131
6.5	Levelized cost of electricity . . . . .	134
6.6	Snapshot power system planning . . . . .	137
<b>7</b>	<b>Discussion and limitations</b>	<b>139</b>
7.1	Strengths and limitations of modeling approach and data . . . . .	139
7.2	Technical and economic implications . . . . .	144
<b>8</b>	<b>Conclusions</b>	<b>153</b>
8.1	Responding to research questions . . . . .	153
8.2	Recommendations . . . . .	162
	<b>Bibliography</b>	<b>165</b>
<b>A</b>	<b>Appendix</b>	<b>I</b>
A.1	Model input data . . . . .	I
A.2	Results tables . . . . .	IV

## Contents

# List of Figures

1.1	Triangle of energy policy goals . . . . .	11
2.1	Life-cycle GHG emissions of power generation technologies . . . . .	19
2.2	Operational range of energy storage systems . . . . .	23
2.3	Structure of the electricity supply system . . . . .	24
2.4	Daily and seasonal variations of European electricity demand . . . . .	26
2.5	Spatially resolved electricity consumption in Europe . . . . .	27
2.6	European spatially disaggregated annual electricity generation . . . . .	29
2.7	Spatially disaggregated European power plant capacity . . . . .	30
2.8	European transmission system cross-border capacities . . . . .	32
2.9	Historic GHG emissions of the energy sector . . . . .	33
3.1	European 18-regions model . . . . .	62
3.2	Approach of the electricity system modeling tool <i>elesplan-m</i> . . . . .	64
3.3	Schematic representation of the electricity system model in <i>elesplan-m</i> . . . . .	67
3.4	Model-internal gas bus . . . . .	76
4.1	Annual electricity generation by wind and PV power . . . . .	99
4.2	Annual regional full-load hours of wind, PV, and hydro power. . . . .	100
5.1	Overview on the transition pathway . . . . .	108
5.2	Power generation capacity mix. . . . .	110
5.3	Annual electricity generation and demand in each planning interval . . . . .	112
5.4	Positive and negative flexibility capacity . . . . .	115
5.5	Spatially disaggregated annual electricity generation and demand . . . . .	116
5.6	Annual exchange electricity between regions . . . . .	117
5.7	Cross-border transmission capacity resulting for 2050 . . . . .	119
5.8	Energy losses in ESSs, transmission system and excess electricity . . . . .	120
5.9	Breakdown of LCOE for each planning interval . . . . .	122
5.10	Breakdown of investment needs . . . . .	123
6.1	Scenario key indicators for 2050 at a glance . . . . .	126
6.2	Scenario results on electricity generation mix for 2050 . . . . .	128

6.3	Energy storage input conversion power among the scenarios . . . . .	129
6.4	Annual electricity exchanges via transmission system . . . . .	133
6.5	Cumulative transmission capacity for scenario variations by 2050 . . . . .	134
6.6	Development of LCOE in scenario variations . . . . .	135
8.1	Sketch of decarbonization pathway . . . . .	163

## List of Tables

2.1	A roadmap of sectoral GHG emissions reduction targets . . . . .	35
3.1	Analysis of current existing energy system models . . . . .	54
3.2	Defined regions and the respective countries . . . . .	63
4.1	Weighted average cost of capital . . . . .	85
4.2	Capital expenditures of power generation technologies . . . . .	87
4.3	Expected lifetimes of power generation technologies . . . . .	87
4.4	Efficiency of power generation technologies . . . . .	88
4.5	Expected development of fuel cost . . . . .	89
4.6	Development of capital expenditures of BESSs . . . . .	90
4.7	Technical and economic parameters of energy storage system technologies . .	90
4.8	Variable cost of CO <sub>2</sub> and system efficiency of PtG . . . . .	92
4.9	Development of capital and operational expenditures of PtG . . . . .	93
4.10	Parameters of gas storages . . . . .	93
4.11	Technical and economic parameters of transmission system . . . . .	94
4.12	Emission factors of power generation technologies . . . . .	95
4.13	EU GHG emissions reduction targets . . . . .	96
4.14	Average electricity demand growth . . . . .	97
4.15	Cumulative power plant capacity in the study region . . . . .	101
4.16	Scenario overview . . . . .	103
4.17	Overview on cost assumptions variations . . . . .	105
5.1	Average full-load hours of nuclear and fossil-based power plants . . . . .	111

# Acronyms

<b>GHG</b>	greenhouse gas
<b>RES</b>	renewable energy sources
<b>CCS</b>	carbon dioxide capture and storage
<b>PV</b>	photovoltaics
<b>CSP</b>	concentrating solar power
<b>PHS</b>	pumped hydro storage
<b>ENTSO-E</b>	European Network of Transmission System Operators for Electricity
<b>EU</b>	European Union
<b>CHP</b>	combined heat and power
<b>CO<sub>2</sub></b>	carbon dioxide
<b>CO<sub>2</sub>eq</b>	carbon dioxide equivalent
<b>UK</b>	United Kingdom
<b>LULUCF</b>	land use, land-use change and forestry
<b>EU-ETS</b>	European Union Emission Trading System
<b>NTC</b>	net transfer capacity
<b>TIMES</b>	The Integrated MARKAL-EFOM System
<b>PRIMES</b>	a computable Price-driven equilibrium Model of the Energy System and markets for Europe
<b>POLES</b>	Prospective Outlook on Long-Term Energy Systems
<b>MARKAL</b>	Market Allocation
<b>EFOM</b>	Energy Flow Optimization Model
<b>LP</b>	linear programming
<i>elesplan-m</i>	European long-term energy system planning model

## List of Tables

<b>CRF</b>	capital recovery factor
<b>CAPEX</b>	capital expenditures
<b>PtG</b>	power-to-gas
<b>SNG</b>	synthetic natural gas
<b>SoC</b>	state of charge
<b>OCGT</b>	open cycle gas turbine
<b>CCGT</b>	combined cycle gas turbine
<b>IPCC</b>	Intergovernmental Panel on Climate Change
<b>WACC</b>	weighted average cost of capital
<b>IRENA</b>	International Renewable Energy Agency
<b>US</b>	United states of America
<b>UNFCCC</b>	United Nations Framework Conventions on Climate Change
<b>PEM</b>	polymer electrolyte membrane
<b>AEL</b>	alkaline electrolysis
<b>OPEX<sub>fix</sub></b>	fixed operational expenditures
<b>OPEX<sub>var</sub></b>	variable operational expenditures
<b>LCOE</b>	levelized cost of electricity
<b>IGCC</b>	integrated gasification combined-cycle
<b>DoD</b>	depth of discharge
<b>AC</b>	alternating current
<b>FLH</b>	full-load hours
<b>NaS</b>	sodium-sulfur battery
<b>Li-ion</b>	lithium-ion battery
<b>ESS</b>	energy storage system
<b>EIA</b>	<i>Energy Information Administration</i>
<b>CAES</b>	compressed-air energy storage
<b>pahesmf</b>	<i>power and heat energy system modeling framework</i>
<b>oemof</b>	open energy modeling framework

<b>DC</b>	direct current
<b>SMES</b>	superconducting magnetic energy storage
<b>HVDC</b>	high-voltage direct current
<b>GDP</b>	gross domestic product
<b>BAU</b>	business as usual
<b>BESS</b>	battery energy storage system
<b>GHI</b>	global horizontal irradiance
<b>GIS</b>	geographical information systems
<b>DSM</b>	demand side management
<b>ETSAP</b>	Energy Technology Systems Analysis Program
<b>IEA</b>	International Energy Agency
<b>LEAP</b>	the Long-range Energy Alternatives Planning system
<b>NEMS</b>	National Energy Modeling System
<b>IAM</b>	integrated assessment model
<b>MILP</b>	mixed-integer linear programming
<b>PTDF</b>	power transfer distribution factor
<b>TSO</b>	transmission system operator
<b>IAEA</b>	International Atomic Energy Agency