A Model for the Environmental Assessment of Time Resolved Electricity Mixes Including Trade

vorgelegt von

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Abstract

The supply of electricity is of vital importance for today's society. Almost all goods, services and everyday life amenities require electrical energy. Furthermore, new sectors and technologies become increasingly dependent on electricity. The growing importance of electricity increases the environmental relevance of electricity production and consumption. The environmental impact of electricity production and consumption can be quantified by using the Life Cycle Assessment (LCA) approach, which takes all relevant stages of electricity production and consumption into consideration.

The electricity market is a complex and ever-fluctuating system with a constant equilibrium between supply and demand. One of the main options to maintain this equilibrium is interregional and international trade. The various forms of electricity trade constitute a difficulty not yet solved when conducting a LCA of electricity consumption. Another problem in LCA is the fact that electricity storage systems can act as consumers as well as producers. Currently, there is no LCA approach available to account for all relevant aspects influencing the environmental impact of electricity consumption. The main research question this study seeks to answer is therefore:

- How can the environmental impact of electricity consumption be quantified with regard to the specific characteristics of the electricity market?

The answer to this question is a comprehensive LCA model called Electricity Market Model (EMM) that is developed in the study at hand. By means of the EMM, it is possible to compute the influence of various forms of trade on the electricity market, and to quantify the environmental impact of storing-in and storing-out of pump storage plants on an hourly basis. By utilising the EMM, it is possible to answer another central research question:

- What is the relevance of the fluctuation of supply and demand for the environmental impact assessment of electricity consumption and how do future developments on the electricity market influence these results?

The relevance of the fluctuation of supply and demand is demonstrated for twelve types of power plants in eighteen representative European countries for the years 2009, 2020 and 2030 by deploying a high-resolution approach. The resulting hourly Life Cycle Inventory (LCI) datasets are compared to existing annual approaches that can be found in current LCA databases. The differences between annual and hourly LCI datasets are significant for some countries.

The most striking fact is that an annual trade balance can lead to a severe miscalculation of electricity consumption emissions. E.g. for greenhouse gas (GHG) emissions in Switzerland the error can be up to 50% if the trade balance is analysed on an annual basis instead of an hourly basis. Hence, it can be concluded that trade is of such significant relevance that it must be considered on a high-resolution basis.

An additional feature of the EMM is the possibility of implementing transit trade and certificate trade addressing the following research question:

- What is the relevance of various types of trade on the environmental assessment of electricity consumption?

A case study on the relevance of transit trade, where data was available for Switzerland, showed that the results gained from a correct allocation of emissions from electricity consumption differ significantly from those formed by current methodological approaches that neglect or use rough assumptions for transit trade. Another case study for the certificate trade of Norway shows an even higher impact. Therefore, it is crucial to consider transit trade and certificate trade for LCI data sets of electricity consumption in order to avoid an underestimation of emissions associated with electricity consumption providing that reliable data is available.

The capability of the EMM to answer the previously mentioned research questions leads to the concluding question that the study at hand wants to answer:

- What are the consequences of the findings of this study for the different stakeholders involved in the environmental impact assessment of electricity consumption?

For a LCA practitioner the use of annual LCI data sets of electricity consumption is the only practicable option unless electricity storage systems are assessed. For the creation of an annual LCI data set of electricity consumption, however, high-resolution background data generally increases precision. The use of high-resolution trade data can reduce calculation errors significantly where no hourly production data is available.

As a result of this study, it can be stated that, with the development of the EMM, it is now possible to provide a distinct and comprehensive method for assessing the environmental impact of electricity consumption with regard to the specific research questions that could not be satisfactorily answered in the past.

Zusammenfassung

Die Versorgung mit Strom ist für unsere heutige Gesellschaft von elementarer Bedeutung. Sowohl die Bereitstellung als auch der Betrieb nahezu aller technischen Produkte benötigen elektrische Energie. Zusätzlich sind neue Wirtschaftszweige und Technologien zunehmend abhängig von der Stromversorgung. Die wachsende Bedeutung von Elektrizität geht mit einer steigenden Umweltrelevanz von Stromproduktion und Stromverbrauch einher. Mit Hilfe der Ökobilanzierung ist es möglich, diese Umweltrelevanz unter Berücksichtigung aller Aspekte der Stromerzeugung und des Stromverbrauchs zu quantifizieren.

Der Strommarkt ist von einer komplexen und ständig fluktuierenden Balance von Angebot und Nachfrage geprägt. Zur Aufrechterhaltung dieses Systems spielt der interregionale und internationale Stromhandel eine große Rolle. Die vielfältigen Strukturen des Stromhandels stellen jedoch in der Ökobilanzierung nicht die einzige erhebliche und bisher ungelöste methodische Schwierigkeit dar:

Weitgehend ungeklärt ist auch die Bilanzierung der Doppelfunktion von elektrischen Speichern, die einerseits als Verbraucher und andererseits als Produzenten innerhalb des Strommarktes fungieren. Somit existiert zurzeit keine wissenschaftlich ausreichende Methode der Ökobilanzierung des Stromverbrauchs. Daraus ergab sich die folgende Hauptforschungsfrage dieser Untersuchung:

- Wie können die Auswirkungen des Stromverbrauchs auf die Umwelt unter Berücksichtigung der spezifischen Eigenschaften des Strommarktes quantifiziert werden?

Zur Beantwortung dieser Frage wurde im Zuge dieser Arbeit das Strommarktbilanzierungsmodell EMM (Electricity Market Model) entwickelt. Dieses Modell ist in der Lage, die Auswirkungen sowohl des Stromhandels als auch der Ein- und Ausspeicherung von Strom auf Umweltbelange stundengenau zu berechnen. Dadurch konnte eine weitere zentrale Forschungsfrage beantwortet werden:

- Welche Relevanz haben die Fluktuationen am Strommarkt auf die Umweltbilanz des Stromverbrauchs und wie verändern zukünftige Entwicklungen dieses Ergebnis?

Die Relevanz der Fluktuationen wurden für zwölf verschiedene Kraftwerksarten in achtzehn repräsentativen europäischen Ländern für die Jahre 2009, 2020 und 2030 mit Hilfe eines zeitlich hoch aufgelösten Ansatzes untersucht.

Die sich daraus ergebenden stündlichen Sachbilanzen wurden mit den in Ökobilanzdatenbanken bisher üblichen, jährlichen Sachbilanzen verglichen. Die Unterschiede zwischen stundengenauen Sachbilanzen und jährlichen Sachbilanzen sind für einige der untersuchten Länder gravierend. Von erheblicher Bedeutung ist die Erkenntnis, dass die Zugrundelegung einer jährlichen Handelsbilanz bei der Berechnung einer Ökobilanz des Stromverbrauchs zu beträchtlichen Fehlkalkulationen führen kann. Die hier ausgeführten Berechnungen belegen, dass die Fehlberechnungen bei der Bestimmung der Treibhausgasemissionen des Stromverbrauchs in der Schweiz bis zu 50% betragen können, wenn statt jährlichen Handelsbilanzdaten, stündliche Handelsbilanzdaten zu Grunde gelegt werden. Als Schlussfolgerung ist festzuhalten, dass die hohe Bedeutung des Stromhandels in hochaufgelöster Weise in die Berechnungen einfließen muss.

Eine weitere Funktion des EMM besteht in der Möglichkeit, Transit- und Zertifikatehandel in der Ökobilanz zu berücksichtigen, um die folgende, weiterführende Forschungsfrage zu beantworten:

- Welchen Einfluss haben die unterschiedlichen Handelsarten auf die Ergebnisse einer Ökobilanzierung des Stromverbrauchs?

Eine Fallstudie am Beispiel Schweiz, für welche sehr genaue Daten zur Verfügung stehen, zeigte, dass eine Nichtberücksichtigung oder grobe Abschätzung des Einflusses des Transithandels zu signifikanten Fehlern bei der Ökobilanzierung des Stromverbrauchs führt. In einer weiteren Fallstudie wurde dargelegt, dass die Berücksichtigung des Zertifikatehandels in Norwegen einen noch größeren Einfluss auf die Ergebnisse der Ökobilanzen hat. Es ist daher unerlässlich, Transit- und Zertifikatehandel -die Verfügbarkeit von genauen Daten vorausgesetzt- bei der Ökobilanzierung des Stromverbrauchs zu berücksichtigen.

Zusätzlich zu der durch das EMM ermöglichten Beantwortung der oben genannten Forschungsfragen war es abschließend erforderlich, die folgende Frage zu beantworten:

- Wie wirken sich die in dieser Studie erarbeiteten Erkenntnisse auf die Praxis bei der Ökobilanzierung aus?

Für die allgemeine Ökobilanzierung ist die Verwendung von jährlichen Datensätzen als Einzige sinnvoll und praktisch. Hiervon ist die Umweltbewertung von Stromspeichertechnologien, bei denen eine zeitlich hoch aufgelöste Analyse erfolgen muss, auszunehmen. Bei der Erstellung von Umweltbilanzen des Stromverbrauchs für Ökobilanzdatenbanken wird durch die

Verwendung hochaufgelöster Hintergrunddaten die Präzision deutlich gesteigert. Hierbei ist es von zentraler Bedeutung, den Stromhandel in möglichst hochaufgelöster Weise zu erfassen, da dieser das Ergebnis maßgeblich beeinflussen kann.

Zusammenfassend kann festgehalten werden, dass es mit der Entwicklung des EMM möglich ist, die Umweltwirkungen des Stromverbrauchs unter Berücksichtigung der spezifischen Eigenschaften des Strommarktes zu quantifizieren, was bisher in diesem Umfang und dieser Genauigkeit nicht möglich gewesen ist.

Resumé

La production d'électricité est d'importance capitale pour nos sociétés. La quasi-totalité des biens, des services et du confort de la vie moderne en dépendent. De même, de nouveaux secteurs et technologies ont un besoin grandissant en l'électricité. L'accroissement du rôle de l'électricité augmente l'impact environnemental lié à sa production et à sa consommation. L'impact environnemental de la production et de la consommation d'électricité peut être mesuré en utilisant le procédé d'analyse du cycle de vie (ACV), qui intègre l'ensemble des étapes clés de production et de consommation.

Le marché de l'électricité est un système complexe et dynamique, qui repose sur un équilibre constant entre production et demande. L'une des options principale pour maintenir cet équilibre concerne les échanges internationaux. Les diverses formes d'échanges d'électricité constituent une difficulté lors d'une ACV de la consommation d'électricité. Un autre problème de l'ACV, est qu'un système de stockage puisse à la fois jouer le rôle de consommateur et de producteur. Aujourd'hui, il n'existe aucune approche qui permette de prendre en compte l'ensemble des aspects qui influencent l'impact environnemental de la consommation d'électricité. La question centrale de recherche à laquelle cette étude tentera de répondre est donc :

- Comment mesurer l'impact environnemental de la consommation d'électricité, en considérant les caractéristiques spécifiques du marché de l'électricité?

La réponse à cette question est l'utilisation d'un nouveau modèle ACV appelé « Electricity Market Model » (EMM), développé dans le cadre de cette étude. L'EMM permet d'analyser l'effet des différents types d'échanges ayant cours dans le marché de l'électricité, ainsi que de quantifier l'impact environnemental heure par heure, du pompage-turbinage des centrales hydroélectriques. L'EMM permet également de répondre à une autre question centrale de recherche :

- Quelle est l'importance des variations de l'offre et de la demande sur l'étude de l'impact environnemental de la consommation d'électricité, et comment les évolutions technologiques peuvent-elles modifier ces résultats?

L'importance des variations de l'offre et de la demande est étudiée pour 12 types de centrales, à travers un panel représentatif de 18 pays européens, pour les années 2009, 2020 et 2030, par

l'utilisation d'un modèle à haute résolution. Les nouveaux résultats horaires de l'inventaire du cycle de vie (ICV) sont comparés aux données annuelles existantes disponibles dans les bases de données ACV. Pour certains pays, les différences entre des données ICV horaires les données ICV annuelles sont significatives.

Le résultat majeur est qu'une erreur importante peut être commise dans le calcul des émissions liées à la consommation d'électricité, lorsque ce calcul se base sur une balance annuelle des échanges. Pour la Suisse, l'erreur peut atteindre 50%, lorsque des données annuelles sont utilisées à la place de données mensuelles.

Une caractéristique supplémentaire de l'EMM, est qu'il permet d'intégrer les transits d'électricité ainsi que les échanges de certificats d'électricité verte, afin de répondre à la question suivante:

- Quelle est l'importance des différents échanges sur l'étude de l'impact environnemental de la consommation d'électricité?

Une étude de cas sur l'effet du transit, utilisant des données disponibles pour le marché Suisse, a montré qu'une différence significative existe dans le calcul des émissions liées à la consommation d'énergie, dès lors qu'une allocation correcte du transit est effectuée, en lieu et place d'une estimation grossière ou d'une simple exclusion. Une autre étude de cas, sur l'impact des échanges de certificats d'électricité verte en Norvège, montre un effet encore plus important. Il est donc crucial, dès lors que des données fiables sont disponibles, de prendre en compte les transits et les échanges de certificats d'électricité verte, dans les bases de données ICV de consommation d'électricité, afin de ne pas sous-estimer les émissions liées à la consommation d'électricité.

La capacité de l'EMM à répondre aux questions précédentes de recherche, aboutie à la question finale à laquelle la présente étude souhaite répondre:

- Quelles sont les conséquences de cette étude pour les différentes parties prenantes, impliquées dans l'étude de l'impact environnemental de la consommation d'électricité?

Pour les professionnels de l'ACV, l'utilisation des données ICV annuelles sur la consommation d'électricité est la seule option pratique, à moins qu'une analyse des systèmes de production et de stockage soit réalisée. L'utilisation de données hautes-résolutions, lors de la création d'une base de données ICV, en augmentera en général la précision. Lorsque des données horaires ne sont pas disponibles, il est possible d'utiliser des données hautes-résolutions sur le transit d'électricité, afin de réduire la marge d'erreur.

Le résultat de cette recherche est qu'il est désormais possible, grâce au développement de l'EMM, de disposer d'une approche unique et représentative pour étudier l'impact environnemental de la consommation d'électricité, dans le cadre des questions de recherches précédentes qui ne pouvaient, jusqu'alors, être résolues de manière satisfaisante.

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List of Abbreviations

AT	Austria (ISO 3166 A 2)
BE	Belgium (ISO 3166 A 2)
CDP	Carbon Disclosure Project
CH	Switzerland (ISO 3166 A 2)
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
CZ	Czech Republic (ISO 3166 A 2)
DE	Germany (ISO 3166 A 2)
DK	Denmark (ISO 3166 A 2)
DSM	Demand Side Management
EECS	European Energy Certificate System
EMM	Electricity Market Model
ENSTO-E	European Network of Transmission System Operators for Electricity
ES	Spain (ISO 3166 A 2)
EWI	Energiewirtschaftliches Institut an der Universität zu Köln (Institute of Energy Economics at the University of Cologne)
FI	Finland (ISO 3166 A 2)
FR	France (ISO 3166 A 2)
GB	Great Britain (ISO 3166 A 2)
GHG	Greenhouse Gas
GWP	Global Warming Potential

HV	High Voltage
IE	Ireland (ISO 3166 A 2)
IEA	International Energy Agency
IT	Italy (ISO 3166 A 2)
kWh	Kilowatt Hour
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LU	Luxembourg (ISO 3166 A 2)
LV	Low Voltage
MV	Medium Voltage
MWh	Megawatt Hour
NL	The Netherlands (ISO 3166 A 2)
NO	Norway (ISO 3166 A 2)
PL	Poland (ISO 3166 A 2)
PT	Portugal (ISO 3166 A 2)
RECS	Renewable Energy Certificate System
RED	Renewable Energy Directive
RES	Renewable Energies
SE	Sweden (ISO 3166 A 2)
TWh	Terawatt Hour
WEO	World Energy Outlook of the IEA

List of Variables

$\vec{c}$	Consumption-Vector
$\vec{c}^{e}$	Consumption-Emission-Vector
$\vec{c}^{e}_{rel}$	Relative Consumption-Emission-Vector
$\vec{\check{c}}$	Corrected Consumption-Vector
$\vec{\check{c}}^{e}$	Corrected Consumption-Emission-Vector
$\vec{\check{c}}^{e}_{rel}$	Corrected Relative Consumption-Emission-Vector
E	Emission-Matrix
$\vec{i}^{e}$	Imported-Emission-Vector
$\vec{p}$	Production-Vector
$\vec{p}^{e}$	Production-Emission-Vector
$\vec{p}^{e}_{rel}$	Relative Production-Emission-Vector
P^{e}_{rel}	Relative Production-Emission-Matrix
${}^{c}\vec{t}$	Contract-Trade-Vector
${}^{c}\vec{t}^{e}$	Contract-Emission-Trade-Vector
${}^{c}\vec{t}^{e}_{rel}$	Relative Contract-Emission-Trade-Vector
${}^{v}\vec{t}$	Virtual Trade-Vector
${}^{v}\vec{t}^{e}$	Virtual Emission-Trade-Vector
${}^{v}\vec{t}^{e}_{rel}$	Virtual Relative Trade-Emission-Vector
T	Trade-Matrix
T^{e}	Emission-Trade-Matrix
${}^{T}_{C}T$	Transit-Correction-Matrix
${}^{v}T$	Virtual Trade-Matrix
$\check{T}$	Final Trade-Matrix

1. Introduction

Electricity is of major importance for today’s society. Almost all goods, services and everyday life amenities require the use of electrical energy. Furthermore, new sectors and technologies become increasingly dependent on electricity. One example for this development is the transportation sector’s introduction of electric vehicles. This is just one example of many, showing that the role of electricity in society steadily increases.

The increasing importance of electricity has to be considered within the context of a rapidly changing European electricity market. Consumers are now able to choose a specific supplier almost regardless of their own location, and decentralised small producers are entering the market in high numbers. Furthermore, new renewable technologies, such as wind and photovoltaic technologies are entering the market on a large scale. These changes lead to an increased interconnectedness and diversification of the electricity market.

Electricity produced by using renewable resources is one of the most effective options for the European Union to reduce greenhouse gas (GHG) emissions. According to the Renewable Energy Directive (RED), by 2030 GHG emissions are to be cut by 60% of their 1990 values, using at least 20% renewable energy within the European Union (European Commission 2009). Each country is required to increase its share of renewable energy. In order to comply with the RED, it is also legal to trade certificates for green electricity certificates without the corresponding amount of electricity.

The German electricity market is transforming even more rapidly as a result of the German government’s decision to shut down all nuclear power plants until 2022 (Deutscher Bundestag 2011). Now, more than 22 GW of installed nuclear capacity need to be replaced by other technologies in order to meet the demands of Germany’s electricity consumption (Bundesministerium für Wirtschaft und Technologie (BMWi) 2012). At the same time, the GHG emission reduction goals of 60% until 2030 must still be achieved (BUNDESMINISTERIUM FÜR UMWELT, Naturschutz und Reaktorsicherheit (BMU) 2007). In order to reach this goal, Germany is forced to invest heavily in renewable energy. The balancing of demand and supply in an electricity market with a high share of renewables is complex, stemming from the fact that the availability of most renewable energy sources, such as solar and wind energy sources, is dictated by meteorological variations. Supply flexibility can be gained through power plant management, trade (which is limited to the capacity of distribution lines) or by using electricity storage systems. Demand is generally inflexible as most industrial processes, services and households require instant electricity availability. There is, however, some potential to shift "peak" demand to "off peak" hours through financial incentives or other options. This demand adjustment called "Demand Side Management" (DSM) can help to adjust the grid load to some extent if exercised on a considerable scale.

The environmental relevance of electricity production and consumption is steadily increasing as a result from the ever-increasing usage of electricity in modern society. It is therefore the goal of this study to introduce a model for quantifying emissions accurately in a dynamic environment such as the European electricity market. The process of emission quantification needs to fulfil current and future scientific requirements to measure environmental impacts associated with electricity production and consumption in a satisfactory way. The most significant factors, which have to be taken into consideration, are:

- Fluctuation of supply and demand
- Interregional trade of physical electricity
- Trade of electricity certificates without the exchange of physical electricity
- Electricity storage systems

In the following chapter, the status quo of methodologies to quantify emissions from electricity production and consumption is analysed, and gaps in the current methodologies are identified with regard to the characteristics of the European electricity market. After the status quo analysis, Chapter 3 outlines the exact goal and procedure of this study.

2. Assessing the Environmental Impact of Electricity Consumption – General Methodologies and Current Status

When assessing the environmental impact of electricity consumption it is crucial to include direct emissions as well as indirect emissions. Direct emissions occur at a power plant when burning fossil fuels. Currently, the European legislation requires electricity producers to publish information about CO_2 emissions and radioactive waste associated with the electricity produced by the supplier in the course of a year (European Commission 2003). These CO_2 emissions, however, do not include indirect emissions from the fuel upstream or the manufacturing of power plants (BAUMERT, M. et al. 2010). In order to provide a holistic approach for the environmental impact assessment of electricity consumption, a consideration of direct and indirect emissions of the manufacturing phase of power plants as well as direct and indirect emissions of the use phase of power plants is necessary. The methodology to cover all these aspects is called Life Cycle Assessment (LCA). In the following chapter, the LCA methodology applied is explained in detail.

2.1 The LCA Methodology

The LCA methodology is standardised in the (ISO 14040 2006) and (ISO 14044 2006) as part of the ISO 14000 environmental management standards series (FINKBEINER, M. et al 2006). The general procedure consists of four phases. Starting with a goal and scope definition, the Life Cycle Inventory (LCI) of a product or service is analysed. The result of an LCI analysis is the quantification of inputs and outputs of a product or a service (ISO 14040 2006). After the quantification of the inputs and outputs, the results are assessed with regard to the impact on the environment. This step is called Life Cycle Impact Assessment (LCIA). Finally, the results of the LCI and the LCIA are interpreted with respect to the goal and scope definition.

Figure 2-1 depicts the phases of an LCA.

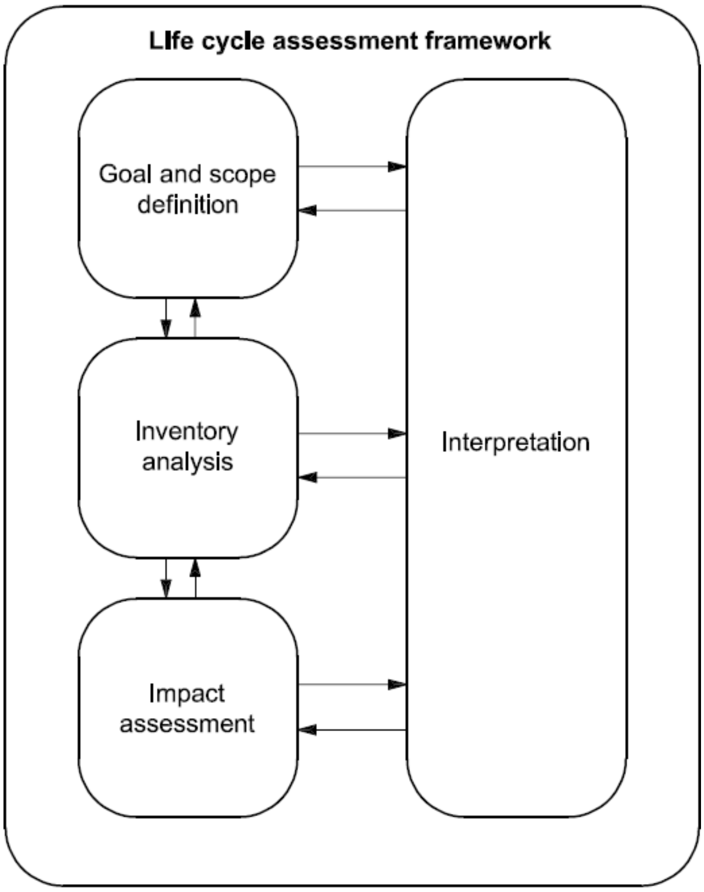

Figure 2-1: Phases of a LCA Taken from (ISO 14040 2006)

A LCA can be applied for any product or service and enables stakeholders to identify the environmental impact caused by the manufacturing of a product or the conducting of a service. The environmental impact can be assessed using a wide range of different categories and the scientific state of the art in environmental impact assessment is published and regularly updated in (GOEDKOOP, M. et al 2009). In the following chapters, the application of the LCA approach for region specific electricity mixes is discussed.

2.2 Production Mix vs. Consumption Mix

There is a range of LCA methodologies available to assess the environmental impact of electricity production. Before everything else, it is crucial to differentiate between emissions caused per unit of electricity produced (defined by the production mix of a certain region) and emissions caused per unit of electricity consumed (defined by the consumption mix of a certain region). The consumption mix includes the electricity imported from, or exported to, regions with different production mixes. When assessing the environmental impact of products, services or organisations the consumption mix is the relevant factor to apply (FINKBEINER, M. 2013). It is to be noted, however, that the production mix can be equal to the consumption mix if no trade is occurring. Main LCA databases such as ecoinvent (ecoinvent Centre 2013) and GaBi (PE International 2013) factor in the consumption mix when providing country specific electricity data. The different methodologies for determining the electricity consumption emissions are therefore discussed in the following chapters.

2.3 Electricity Trade

Electricity trade can strongly influence the environmental impact of electricity consumption, since indirect emissions are traded (see Scope 2 RANGANATHAN, J. et al 2004) between different countries/regions. Specific production emissions can vary significantly between different countries (e.g. Poland with an annual average of 1.11 kg/kWh vs. Norway with 0.05 kg/kWh PE International 2013) and trade can therefore lead to a substantial shift of indirect emissions (MARRIOTT, J. et al. 2005). Since the liberalisation of the European electricity market had begun in 1996 (European Commission 1996), the trade of electricity has grown rapidly. At the present day, electricity consumers are able to choose their electricity supplier without being restricted to regional choices. Furthermore, small suppliers entered the market, offering a larger spectrum of green products (GREEN, R. 2006).

There are two basic types of electricity trade between producers and consumers:

1. **Electricity Trade with Physical Delivery (Linked Approach) (TIMPE, C. 2007), (TIMPE, C. 2009) and (TIMPE, C. et al. 2009):**

   Electricity is purchased from a certain producer who feeds the corresponding amount into the grid. Electricity attributes (e.g. CO_2 emitted), which are traded together with the corresponding physical electricity volume, are traded as part of the so-called linked approach.

2. Electricity Trade Using Solely Attributes (Virtual Trade or the De-linked Approach[1] TIMPE, C. 2007, TIMPE, C. 2009 and TIMPE, C. et al. 2009):

Physical electricity can be sold separately from its attributes by using green certificates/guarantees of origin. In this case, attributes describe the origin of the electricity, which can for instance be a renewable source such as wind- or waterpower. This origin also defines the emissions associated with electricity production. The consumer purchases only electricity attributes, e.g. from the Renewable Energy Certificate System (RECS) (RECS International 2012) or the EECS (European Energy Certificate System) (RECS International 2012) without a physical electricity delivery. With the introduction of RECS in 2002, a second, independent, market for electricity attributes (virtual trade) was created in addition to the market for trade of physical electricity.

[1] The expressions 'virtual trade' and 'de-linked approach' are used synonymously in this study.

Figure 2-2 visualises the basic types of electricity trade between producers and consumers.

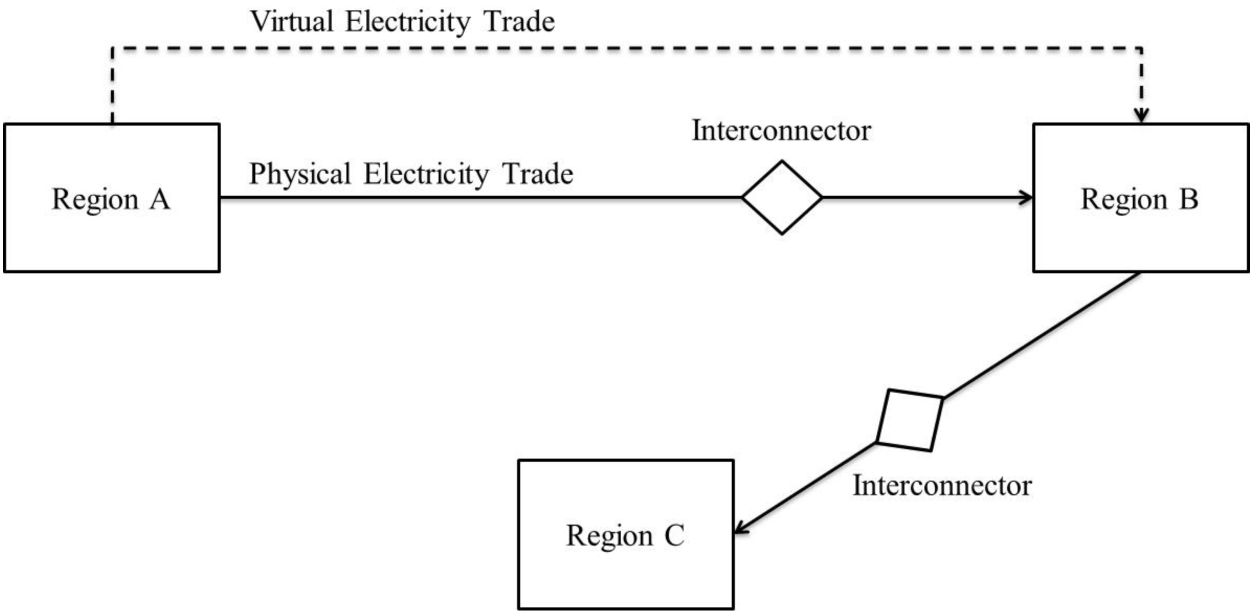

Figure 2-2: Types of Electricity Trade Between Producers and Consumers

The trade of electricity between supplier and consumer via the linked approach appears in the interconnector balance of the grid operator in each country/region. An interconnector is defined as a cable connecting two independent electricity grids (TURVEY, R. 2005). This data is collected for most of Europe and published by Eurostat (Eurostat 2013), local transmission network operators, or by the European Network of Transmission System Operators for Electricity (ENTSO-E) (European Network of Transmission System Operators for Electricity (ENTSO-E) 2013). In most cases, the time resolution is 15 minutes. When analysing the physical flows of electricity through interconnectors, however, it is impossible to distinguish whether the electricity has actually been produced in the neighbouring connected country or whether it has just been transited through the connected neighbouring country. Furthermore, the de-linked approach cannot be assessed at all with the method of measuring physical electricity flows. Therefore, both the transit trade and the virtual trade have to be evaluated separately.

There are different methodologies available to analyse electricity trade and to assess the environmental burdens related to the consumption of electricity. These methodologies differ significantly depending on their respective focus in the context of electricity imports, exports and transit flows. (MÉNARD, M. et al. 1998) and (FRISCHKNECHT, R. et al. 2010) give a very good overview of current approaches in the LCA community in order to assess the environmental impact of electricity consumption. The following chapters describe different models of electricity trade schemes based on (MÉNARD, M. et al. 1998).

2.3.1 Trade Model 1

In Trade Model 1, trade does not influence the consumption mix. The emissions associated with electricity production in a region are equal to the consumption emissions of electricity as visualised in Figure 2-3.

Figure 2-3: Trade Model 1: "Consumption Mix = Production Mix" After (MÉNARD, M. et al. 1998)

This approach can be used if a supplier mix is directly delivered to the customer without an external exchange. This could be the case for a supplier, a customer, or within a country without a connection to another electricity system, such as Iceland.

2.3.2 Trade Model 2

Trade Model 2 is based on the assumption that the consumption mix is equal to the export mix. Imported electricity is added to the local production mix before it is exported. Figure 2-4 depicts Trade Model 2.

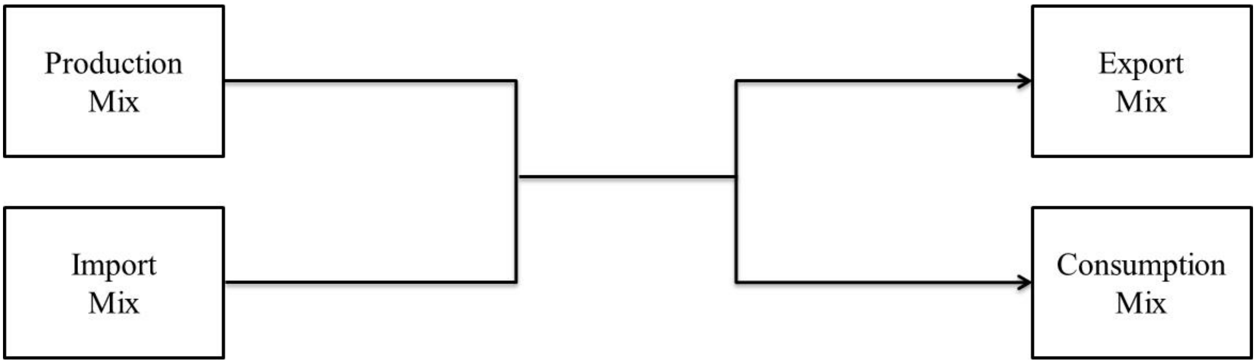

Figure 2-4: Trade Model 2: "Consumption Mix = Production Mix + Import Mix = Export Mix" After (MÉNARD, M. et al. 1998)

This approach can be iterated. For the first iteration, the export mix of each country/region is equal to the production mix since no imports were considered so far. Hence, the import mix is equal to the production mix of the country/region from which the electricity is imported. For a second iteration, the import mixes can contain electricity from non-neighbouring countries/regions. As a result, the transit trade of electricity can be considered through iteration.

PE International, one of the major LCA database suppliers, uses this iterative Model 2 approach (PE International 2013), (VIEBAHN, P. et al 2007) and (BENDEL, D. 2012).

2.3.3 Trade Model 3

For Trade Model 3, the export mix is equal to the production mix (see step 1 in Figure 2-5). After the export of electricity, the import mix adds up to the remaining production mix, resulting in the consumption mix (see step 2 in Figure 2-5).

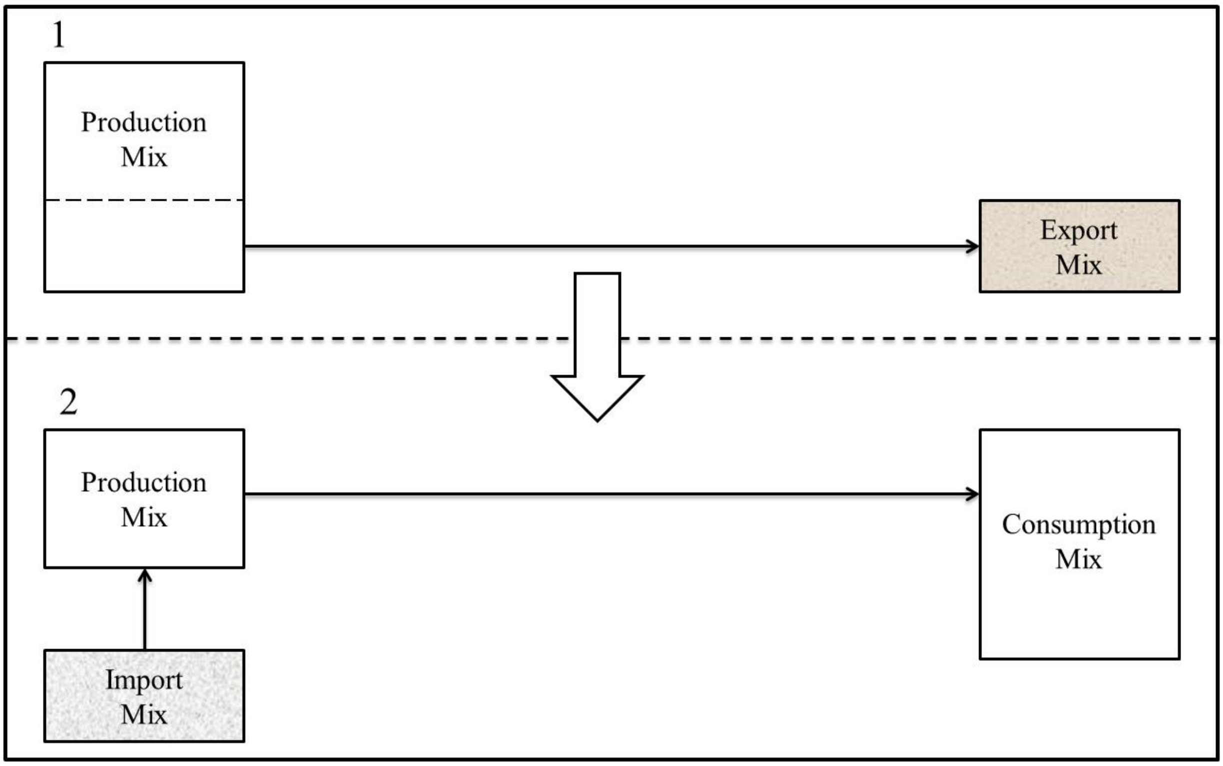

Figure 2-5: Trade Model 3: "Consumption Mix = Production Mix – Export Mix + Import Mix -> Export Mix = Production Mix" After (MÉNARD, M. et al. 1998)

In this model, the production mix is exported. Imports are added to the consumption mix and are not exported which is the reason why transit flows are not considered. Consumption mixes in the ecoinvent Database are determined using Model 3: "[...] imported electricity is estimated with the production mixes of the exporting countries. [...]" (DONES, R. et al 2007). In consequence, ecoinvent does not consider transit flows.

2.3.4 Trade Model 4

In Trade Model 4, only net trade flows are considered as shown in Figure 2-6. If the imports are higher than the exports, only the difference between both account for the consumption mix. If the exports are equal or higher than the imports, the consumption mix is equal to the production mix, as well as to the export mix.

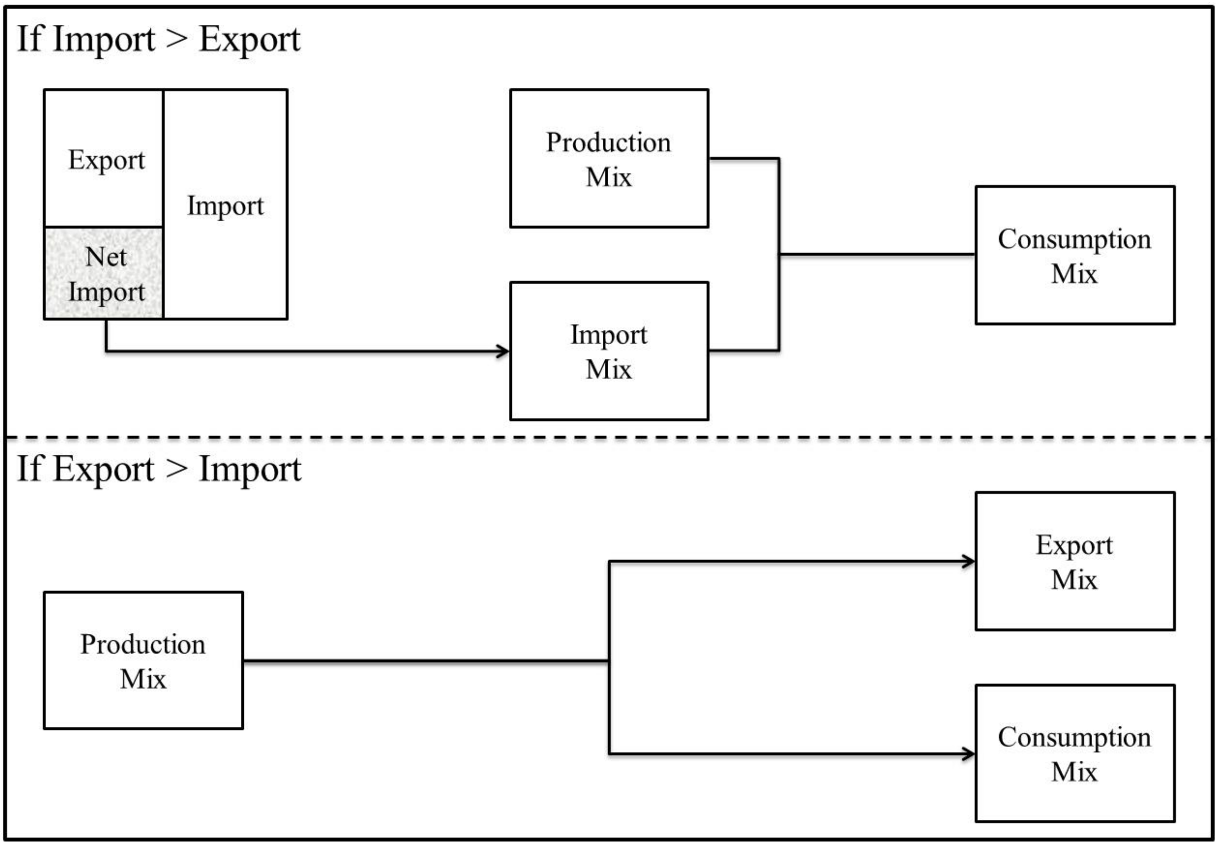

Figure 2-6: Trade Model 4: "Consumption Mix = Production Mix + Net Import Mix" After (MÉNARD, M. et al. 1998)

It needs pointing out that none of these models provides satisfactory results for the consideration of transit trade. A clear outcome is only possible where the exact amount of transit trade, including origin and destination, is known. Furthermore, de-linked electricity trade is not taken into account. The currently missing consideration of the transit trade, as well as the trade of electricity certificates in current LCA databases is therefore the subject of investigation within Chapters 4.2 - 4.6 of this study.

The examples evaluated above show that not only the amount of traded electricity is relevant but also the timing of the electricity traded. This fact leads to the conclusion that time resolution plays an important role, too, when it comes to the assessment of electricity usage-related environmental impact. Hence, the following chapter takes a closer look at the impact of time resolution on the LCA of electricity.

2.4 Time Resolution

Most of the LCA databases such as the GaBi Database or the ecoinvent Database provide annual average LCI data. However, with respect to the dynamics in supply and demand of the electricity market, an annual average may not provide a sufficient resolution application running on a seasonal or hourly basis. (MÉNARD, M. et al. 1998) states that seasonal approaches can be used for applications running during a specific time of the year, e.g. heat pumps in winter or air conditioners in summer. Approaches based on daily variation are suggested to be used for night trains or business units.

Further LCA studies with respect to a high time resolution (hourly) electricity production and consumption can be found in (WEBER, C. et al. 2010), (SZCZECHOWICZ, E. 2011a) and (SZCZECHOWICZ, E. 2011b). There, products with a specific time-related function consuming electricity, such as night heat storage and the charging of electric cars are examined in detail. These studies conclude that differences between emissions calculated on an annual average and emissions calculated using a high time resolution are less than 5% for GHG emissions (SZCZECHOWICZ, E. 2011a). Other impact categories such as Eutrophication Potential (EP) can differ up to more than 30%. The differences are expected to increase in the future, as higher shares of electricity from renewable sources result in stronger variations of emissions during the day. Both papers focus only on Germany and do not account explicitly for the trade with other European countries. Electricity trade, however, has a major influence on the LCA of electricity consumption. Moreover, the emissions accounted for pump storage are very high, as coal power plants assumedly mainly provide pump storage during off-peak hours. This assumption derives from a LCA methodology called "consequential LCA" which is explained in Chapter 2.5. Other current approaches to compute the emissions derived from pump storage are mainly based on annual averages of electricity consumption. In order to solve this problem, a higher time resolution is required, making it possible to understand and assess storage mechanisms correctly from a LCA perspective. This assessment must also include import and export mechanisms which can be described more accurately using a high temporal resolution as the trade flows and directions can change significantly within a short period of time.

The currently missing consideration of the storage as well as dynamics in electricity supply and demand is therefore a subject of investigation within this study. Data availability is, however, an important issue. There is no publicly available database on hourly production data for each of the power plant types in Europe. Hence, the data required has to be modelled using appropriate models. The following chapter provides a description of these models.

2.5 Attributional LCA vs. Consequential LCA

After having decided on a trade model and a temporal resolution the LCA practitioner has to choose between two main categories of LCA interpretation methodologies: the attributional LCA and the consequential LCA. The attributional LCA generates a Life Cycle Inventory (LCI) of input and output flows associated with (or attributed to) the production of e.g. one kWh of electricity (GUINÉE, J. B. et al 2002). The system's input and output increases linearly with the amount of electricity consumed. The LCI of a consequential LCA, however, quantifies system outputs as a result of a change (FINNVEDEN, G. et al 2009), e.g. when large scale Demand Side Management (DSM) is introduced to the electricity market. For example, some LCA studies use electricity from coal power plants to provide the base load to model electricity consumption by pump storage. This is because pump storage increases the base load demand. With various scenarios of demand change in customer behaviour, the changes of power plant usage are quantifiable by using an appropriate agent-based model (see Chapter 2.6). As a result, the power plants covering the higher demand are mainly coal power plants. A consequential approach therefore generally requires a comparison of two scenarios in order to assess the impact of a behaviour change.

One of the most popular consequential approaches as a background system in LCA studies is the marginal electricity mix as applied e.g. in (MÉNARD, M. et al. 1998), (PEHNT, M. et al 2011), (MATHIESEN, B. V. et al 2009), (HARTMANN, N. et al. 2011), (HELMS, H. et al 2011), (LUND, H. et al 2010) and (ZIMMER, W. et al 2011). A marginal electricity mix can be computed for a short-term period as well as for scenario modelling for future electricity markets. 'Short-term' means that the marginal electricity mix uses a high time resolution and is the result of the deactivation and activation of existing power plants due to a short-term change in demand.

Consequential approaches focusing on long-term effects, however, are analysed by a scenario modelling for future electricity markets. These models do not only quantify the deactivation and activation of existing power plants but also the building of new power plant capacities according to defined scenarios. These scenarios are, amongst other factors, influenced by future electricity demand and a consumption pattern. This change in demand can be induced by emerging technologies adding up to the existing demand, e.g. e-mobility.

Two examples of consequential LCA modelling on e-mobility can be found in (PEHNT, M. et al 2011) and (ZIMMER, W. et al 2011). Both studies use high-resolution energy economic models, which simulate different scenarios for the years 2020 and 2030. These LCAs, however, are not ISO 14040/44 compliant (PEHNT, M. et al 2011), very sensitive to the assumptions chosen, and therefore of limited robustness (MÉNARD, M. et al. 1998).

The study at hand focuses on the provision of electricity and not on the consequences of a change in behaviour. Hence, the attributional LCA approach is applied in the following chapters.

2.6 Agent-based Modelling of Electricity Markets

Agent-based models are able to simulate actions and interactions of autonomous individuals (agents) to assess their effects on the system as a whole. It constitutes a method that has been successfully applied in the past to the analysis of e.g. the dynamics of traffic or human behaviour (MUAZ, N. et al. 2011), (JARVIS, P. et al 2010) and (BONABEAU, E. 2002). Since the electricity market consists of different agents (producers, consumers etc.), these models are particularly suitable for the simulation of electricity systems (GUERCI, E. et al. 2010), (63), (WEISHAAR, N. et al. 2009) and (ZHOU, Z. et al. 2007). There are many different models available for a wide range of regions in the world (Wagner S. L. et al. 2006), (BAGNALL, A. J. et al. 2005), (WEIDLICH, A. et al. 2008), (BUNN, D. W. et al. 2001), (RASTEGAR, M.A et al. 2010) and (KAN, S. et al. 2010). In this context, the DIMENSION Model (EWI 2011) is the most suitable one for this study. Since the first development of the DIMENSION Model in 1996, it has been continuously refined and enhanced by new modules to cover a wide range of issues regarding the European electricity market (RICHTER, J. 2011). For this study, the DIMENSION Model is able to provide electricity production and electricity trade data in an hourly resolution. Moreover, DIMENSION is able to simulate future scenarios for the European electricity markets.

The following chapter provides a summary of the current status quo of research and defines the resulting research questions to be answered in the study at hand.

2.7 Summary of the Status Quo and Research Questions

In Chapter 1 the current situation of the European electricity market is analysed and four main factors influencing the environmental assessment of electricity consumption are identified:

- Fluctuation of supply and demand
- Interregional trade of physical electricity
- Trade of electricity certificates without the exchange of physical electricity
- Electricity storage systems

With regard to these main factors, existing LCA approaches assessing the environmental impact of electricity consumption are analysed. A number of current studies analyses these factors as described in the previous chapters. In conclusion, no study presents satisfactory solutions for all four main factors influencing the environmental impact of electricity consumption. Therefore, the main research question posed in this study is:

- How can the environmental impact of electricity consumption be quantified with regard to the specific characteristics of the electricity market?

The answer to the main research question lies in the development of an Electricity Market Model (EMM) capable of accounting for the characteristics of the electricity market. For the design of the EMM, follow-up questions with regard to the relevant characteristics of the electricity market need to be addressed:

- How can the Life Cycle Inventory data of electricity production be implemented (see Chapter 4.1)?
- What types of electricity trade exist and how can these trade relations be incorporated into the EMM (see Chapters 4.2 - 4.6)?
- How can the environmental impact of electricity storage systems be assessed and integrated into the EMM (see Chapter 4.7)?

In the interest of LCA practitioners and database providers, it is crucial to evaluate the relevance of each aspect influencing the LCA of electricity consumption. To achieve this, the following research questions are addressed in the modelling of the environmental impact assessment of electricity consumption:

- What is the relevance of the fluctuation of supply and demand for the environmental impact assessment of electricity consumption and how do future developments on the electricity market influence these results (see Chapter 5)?
- What is the relevance of various types of trade on the environmental assessment of electricity consumption (see Chapter 6)?
- What are consequences of the results of this study for the different stakeholders involved in the environmental impact assessment of electricity consumption (see Chapter 7)?

After the elaboration of these questions, the study closes with a discussion about the limitations of this study and an outlook for possible future developments.

It has to be noted that this study does not aim to fully assess and explain mechanisms on the European electricity markets. For some examples, explanations are provided. These explanations, however, are not intended to be exhaustive. High-resolution production and physical trade data is provided by the DIMENSION Model. Since the DIMENSION Model is able to deliver almost all relevant electricity production, consumption and trade data, the public data availability is not a central subject of investigation in this study. There is, however, a short section dealing with the subject of data availability in Chapter 7.6.

The following chapter provides a further specification of the general goal and the procedure of the study at hand.

3. Goal and Procedure

The goal of the study is to answer the main research questions articulated in Chapter 2.7. In order to do so it is crucial to provide a scientific framework for the life cycle based environmental impact assessment of electricity consumption that can account for a fluctuating production pattern due to an increasing share of renewables, electricity storage and interregional trade. Once the scientific framework is evaluated in Chapter 4, the findings are implemented into the EMM, a tool that enables the user to define temporal and spatial resolutions as required for an accurate LCA of electricity consumption. As a result, the LCI associated with electricity consumption can be determined using a variable time resolution.

Based on the EMM, a case study for Europe is done. In order to run the EMM, data on electricity production and electricity trade in high time resolution is needed. There is, however, no publicly available source on hand to deliver this data. Therefore, a model is required to simulate a high-resolution European electricity market. There are several models available such as the DIMENSION Model developed by the Institute of Energy Economics at the University of Cologne (EWI 2011). The DIMENSION Model is the most suitable one for this study as it covers all relevant European countries and all relevant power plant types as described in Chapter 2.6. It is able to model the production of every single power plant in Europe on an hourly basis as a response to a given demand, including the storing-in and storing-out of existing pump storage plants. Furthermore, all trade flows between European countries are quantifiable on an hourly basis. It is to be noted that the DIMENSION Model is modelling the European electricity market. Therefore, the hourly power plant and trade data can slightly differ from actual statistical data. Figure 3-1 depicts the countries modelled in the DIMENSION Model for this study.

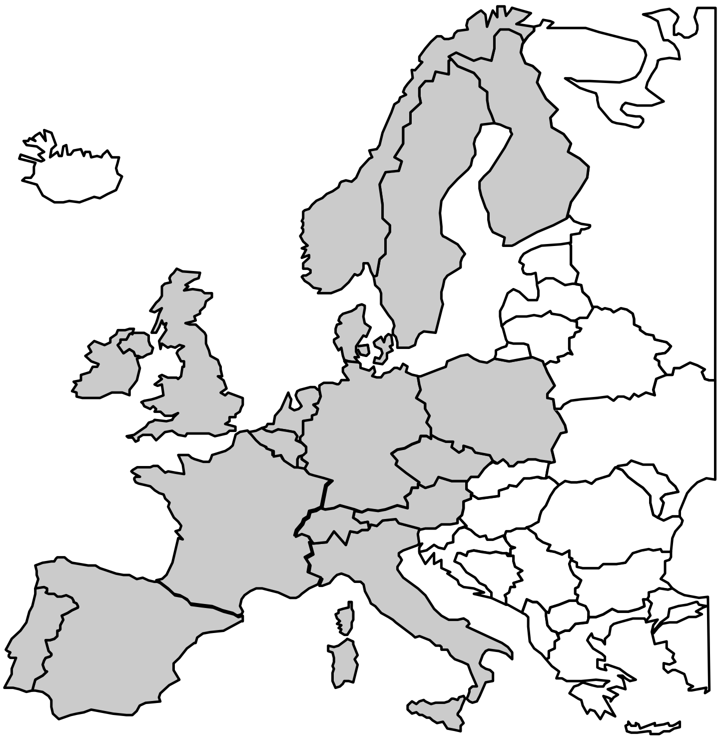

Figure 3-1: Countries Modelled in the DIMENSION Model (EWI 2011)

The eighteen countries modelled are the main countries of the European Network of Transmission System Operators for Electricity (ENTSO-E) and define an enclosed system within the DIMENSION Model. This is a realistic assumption, as the trade between countries marked in grey and white is generally very low (Eurostat 2013). The simulation results of the DIMENSION Model are then transferred as data basis into the EMM as described in Chapter 4.8.

Subsequently the differences between existing LCA approaches and the methodology developed in this study are compared for the countries modelled. This comparison of countries is important since the respective local electricity markets of European countries differ significantly. In order to assess the relevance of future developments of the European electricity market, it is necessary to model future scenarios. The DIMENSION Model is able to simulate the future situation of the electricity market. For the study at hand, the simulation is done up to the year 2030 where the reliability of prediction can be considered as reasonably high. For an intermediate step the year 2020 is chosen. The evaluation of these scenarios is crucial to understand the implication of future changes of the European electricity market on the LCA of electricity production and consumption.

As a result all input and output flows are quantified and the four impact categories are assessed according to the scientific state of the art as described in (GOEDKOOP, M. et al 2009):

- Global warming potential on a 100 year scale (GWP 100)
- Acidification potential (AP)
- Eutrophication potential (EP)
- Photochemical ozone creation potential (POCP)

Chapter 0 of the study examines all the variations of electricity production emissions GWP amongst the countries analysed. Following that, the impact of physical trade is analysed and major implications on the consumption mix are discussed. By using a high time resolution, the consumption emissions and existing pump storage applications in Europe are analysed and the most significant results are discussed in Chapter 5.1.2. A separate section in Chapter 6 deals with the impact of transit trade and virtual trade on an environmental impact assessment of electricity consumption. In Chapters 7.1 – 7.4 the consumption mix is analysed with regard to the implication on LCA results of products and services.

Finally, Chapter 7.6 concludes this study with regard to the research questions expressed in Chapter 2.7 and recommendations for the future.

The following Chapter describes the structure and the mathematical basis of the EMM.

4. Model Development

The EMM consists of two main parts of which one is the LCI data of electricity production. This first part delivers LCI data for each country´s specific electricity production mixes. In order to attain specific electricity consumption mixes, the LCI data of the electricity production mixes are fed into the EMM. Figure 4-1 provides a graphical overview of the basic model structure.

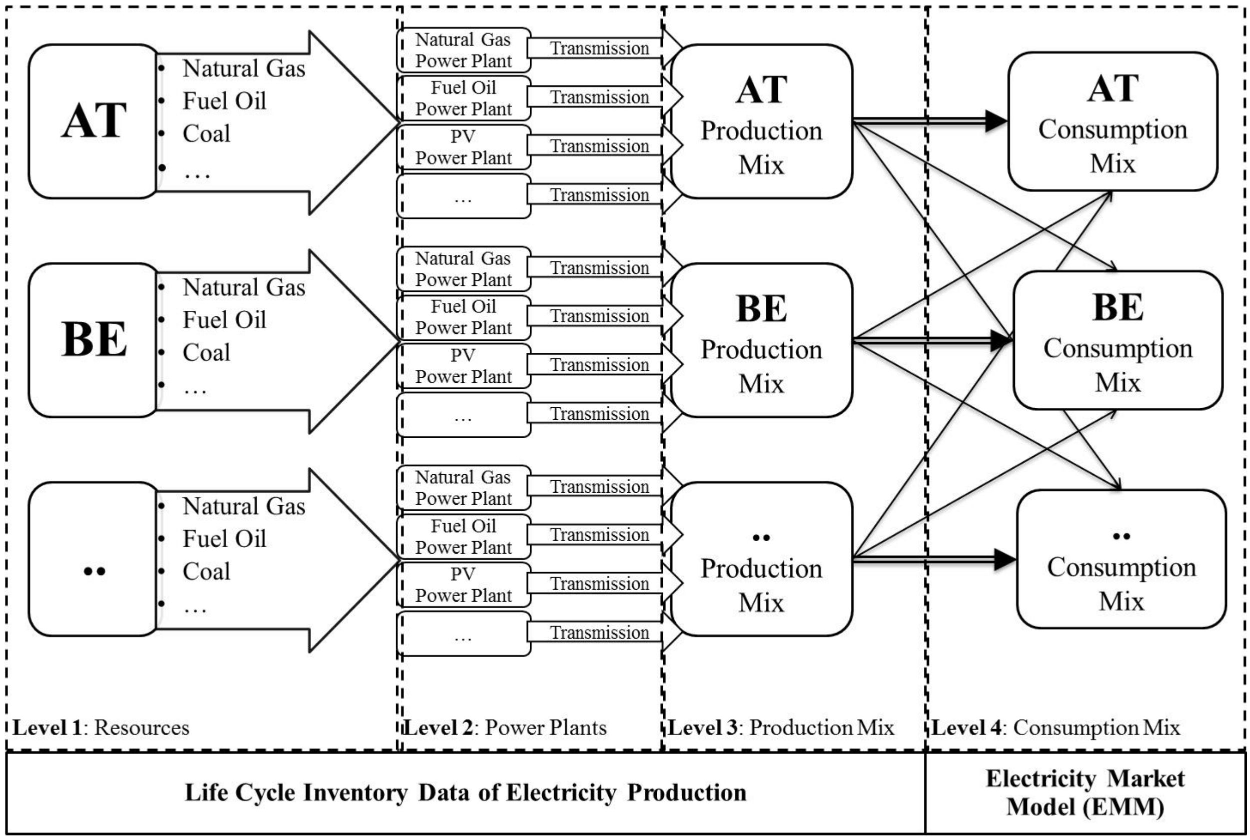

Figure 4-1: Basic Model Structure

The basic model structure shown above describes the system boundary for the LCA. The system boundary is divided into four parts (Levels), each connected by transport and transmission processes respectively. All three Levels require detailed LCI data. The most complete of all LCA databases for this matter is the GaBi Database (PE International 2013) which provides relevant data for most of the European countries.

In Level 1, the upstream of resources and energy carriers needed to build and to fuel power plants are examined. Level 2 analyses the electricity production depending on the fuel type and power plant efficiency for each country. The electricity is then transmitted into a pool called production mix. This production mix is country specific and brought to the electricity market. The electricity market in Europe is not only open to domestic consumers but also foreign consumers can buy from the production mix of a country. These trade mechanisms are considered in Level 4, the EMM where the country specific consumption mixes are determined. Since none of the existing trade models described in Chapter 2 sufficiently account for electricity trade, Chapter 4.3 – Chapter 4.5 evaluate an entirely new trade model.

The following chapters describe each of the Levels in more detail.

4.1 Life Cycle Inventory Data for Electricity Production

4.1.1 Level 1: The Resources

The provision of resources and energy carriers includes the exploitation, the transport and the processing of resources such as crude oil, natural gas, iron ore and many more. In order to run the power plants a fuel is needed which consists of country specific mixes for coal, natural gas, fuel oil, etc. The consumption of these resources represents the primary energy demand (HESSELBACH, J. et al. 2012).

4.1.2 Level 2: The Power Plants

Power plants are the most important part of the LCI of electricity production. Level 2 (emissions from building and running the power plants) accounts for more than 95% of the total system emissions (PE International 2013). There is a wide range of power plant types in use within Europe, of which each has different efficiencies.

Similar technologies using the same fuel are aggregated to specific power plant types where country specific averages on power plant technologies are applied. Table 4-1 shows the power plant types considered within this study with typical efficiency ranges (if applicable) for the European countries considered.

Table 4-1: Types of Power Plant

Type of Power Plant	Efficiency Range (Joint Research Centre (JRC) 2011)
Nuclear	n.a.
Lignite	33% - 39%
Hard Coal	20% - 41%
Natural Gas	24% - 50%
Fuel Oil	20% - 46%
Biogas	22% - 37%
Biomass	16% - 40%
Wind	n.a.
Solar	n.a.
Water Power	n.a.
Geothermal	n.a.

The efficiencies include own electricity consumption used to run the power plant (e.g. for pumps). There is no efficiency factor for renewable and nuclear energies since the “fuel” does not have a heating value.

4.1.3 Level 3: The Production Mix

On Level 3, the production mix is defined. The production mix quantifies the shares of different technologies used to produce one kWh of electricity for each country. The following chapter describes the procedure to determine the emissions associated with the electricity production mix.

4.1.3.1 General Procedure

Each power plant type has typical emission factors when producing electricity. Based on the technology share an LCI for each of the production mixes can be computed. Figure 4-2 depicts a simplified example of this calculation for the GHG emissions of a fictive region.

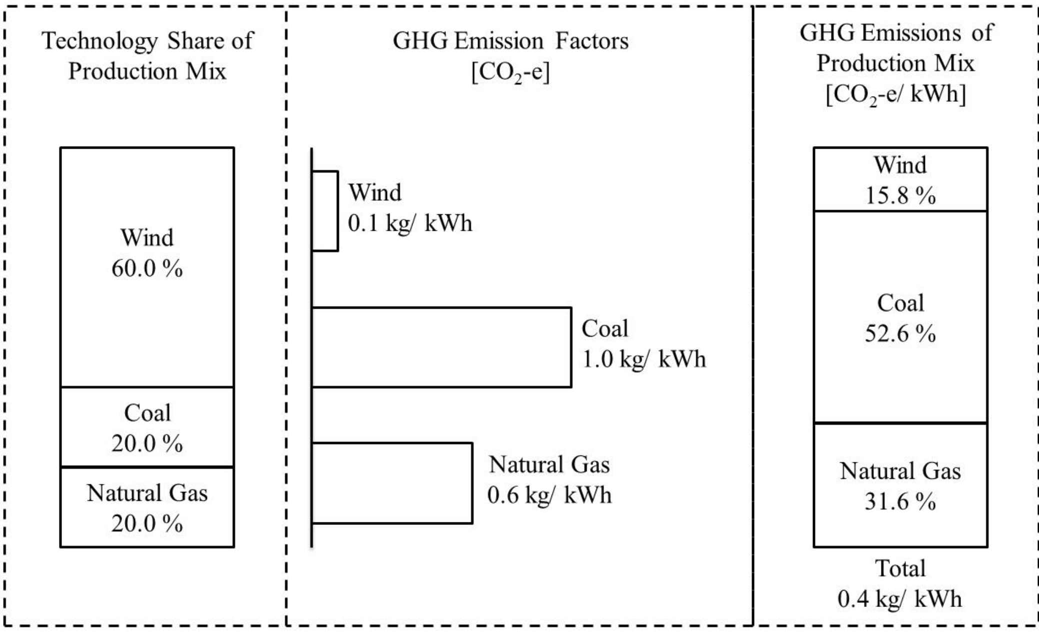

Figure 4-2: Calculation of GHG Emissions of the Production Mix

Here the total GHG emissions produced within a country are computed as an average of 0.4 kg Carbon Dioxide equivalent (CO_2-e) per functional unit (one kWh). The emission factors include Level 1 and Level 2 emissions as well as the own consumption of the power plants. The example region produces electricity through a technology share of 60% wind, 20% coal and 20% natural gas with technology specific emission factors of 0.1 kg CO_2-e/kWh, 1.0 kg CO_2-e/kWh and 0.6 kg CO_2-e/kWh, respectively. As a result, one kWh of electricity produced in that region is at 0.4 kg CO_2-e of which more than 50% originate from coal power plants.

4.1.3.2 Consideration of Distribution Losses

Distribution losses due to the transformation and the distribution of electricity are country specific. Table 4-2 shows the country specific transmission losses at low voltage (end consumer) level.

Table 4-2: Distribution Losses in the Main ENTSO-E Countries (Eurostat 2012) and (World Bank 2013)

Country	Distribution losses (LV)	Country	Distribution losses (LV)	Country	Distribution losses (LV)
Austria	7.0%	Spain	5.6%	Luxembourg	3.9%
Belgium	6.6%	Finland	4.6%	Netherlands	5.4%
Switzerland	9.0%	France	10.2%	Norway	8.7%
Czech Republic	9.5%	Great Britain	10.3%	Poland	13.2%
Germany	6.3%	Ireland	10.2%	Portugal	9.7%
Denmark	9.2%	Italy	8.7%	Sweden	9.8%

It is worth noting that the distribution losses listed in Table 4-2 are annual average values. Short-termed variations can occur because of respective changes of the types of power plants, producing the electricity required in a region or country. A high share of electricity produced on a lower voltage level such as from Wind or Solar generally increases distribution losses. Reliable high-resolution values, however, cannot be computed within this study due to a lack of data availability. Distribution losses vary significantly between different countries. Countries with comparably old infrastructure on transformation and transmission such as Poland tend to have higher distribution losses (SHORT, T. A. 2003) and (HADJSAÏD, N. et al. 2011). Furthermore, highly centralised electricity markets such as that of France require longer distances of travel for electricity, hence, resulting in higher transmission losses than rather decentralised systems (LAKERVI, E. et al. 1995) and (SHORT, T. A. 2003). Distribution losses include losses occurring through the transmission lines as well as the transformation into various voltage levels. Generally, the end consumer is connected to the low voltage (LV) grid, where the losses are the highest (SHORT, T. A. 2003). Appendix A provides a detailed table for distribution losses on different voltage levels.

4.1.3.3 Installed Capacity of Power Plants vs. Electricity Production

For an accurate LCA it is crucial to differentiate between the installed capacity of a power plant and the actual production. The installed capacity of any type of power plant is quantified in Watt (W). It is an indication on how much work a power plant is capable of doing. The work output, however, is Watt-hour (Wh). Therefore, a power plant with a capacity of one W can generate one Wh within one hour, assuming full load. The time of the power plant running at full load varies significantly between technologies and the market structure. Full load hours are quantified by:

$$Full\ Load\ Hours\ [h] = \frac{\text{Electricity Produced Annually } [\frac{\text{Wh}}{\text{8760 h}}]}{\text{Installed Capacity [W] x 8760 h}}$$

The rate of full load hours over a year is defined as:

$$Rate\ of\ Full\ Load\ Hours\ [\%] = \frac{\text{Full Load Hours [h]}}{\text{8760 Hours [h]}}$$

The rate of full load hours of the power plant depends on its availability and how often it is needed. This also includes implicitly the price of the electricity generation, as expensive electricity is only competitive during times of high demand.

Table 4-3 gives an overview of installed capacities, electricity production and the full load hours of different power plant types in Europe for 2009 as an example.

Table 4-3: Installed Capacities, Electricity Production and the Full Load Hours of Different Power Plant Types in the Main ENTSO-E for 2009 According To (Eurostat 2013) and (EWI 2011)

Type of Power Plant	Installed Capacity [GW]	Electricity Produced [GWh]	Full Load Hours [h]	Rate of Full Load Hours
Nuclear	125.3	940,875	7,507	**85.7%**
Hard Coal	126.2	584,715	4,634	**52.9%**
Lignite	42.0	234,695	5,591	**63.8%**
Natural Gas	217.9	632,416	2,902	**33.1%**
Fuel Oil	50.4	4,644	92	**1.1%**
Pump Storage	39.2	12,584	321	**3.7%**
Water Storage	92.4	274,092	2,967	**33.9%**
Run of River	37.2	170,344	4,575	**52.2%**
Wind	73.5	130,298	1,773	**20.2%**
PV	15.8	14,024	885	**10.1%**
Waste	6.1	46,728	7,673	**87.6%**
Biomass	13.5	58,986	4,364	**49.8%**
Biogas	5.0	29,587	5,910	**67.5%**
Geothermal	1.5	5,547	3,743	**42.7%**

For a LCA of electricity production the actual amount of electricity produced within a year has to be used. The major LCA databases (ecoinvent Centre 2013) and GaBi (PE International 2013) use statistics on how much electricity has been produced by each technology. A comparison of installed capacity for different types of power plants is of limited informative value as the rate of full load hours can differ significantly. Hence, the amount of electricity produced within a certain period of time is determining the production mix.

4.2 From the Production Mix to the Consumption Mix - The EMM

For a LCA of electricity consumption the country specific production mixes evaluated in Chapter 4.1 need to be converted into consumption mixes. In order to do so, the electricity trade between the countries needs to be looked at more closely. As described in Chapter 2.3 electricity trade strongly influences the environmental impact of electricity consumption since indirect emissions are being exchanged (see Scope 2 of the GHG Protocol[2] FINKBEINER, M. 2009 and RANGANATHAN, J. et al 2004). With the progressing liberalisation of the electricity market, each market participant is able to buy and sell electricity within the whole of Europe.

4.2.1 Types of Electricity Trade

In the DIMENSION Model (EWI 2011), physical electricity flows between the countries can be simulated. There is, however, no option to trace back each electron to the source of its generation regarding transit trade or direct sales to consumers. Therefore, the DIMENSION Model data has to be corrected by electricity that is only transiting or that is directly delivered from the producer to the consumer and that is not available to the public market.

Furthermore, the virtual trade of electricity cannot be described with physical electricity flow data. Hence, it needs to be considered separately as described in Chapter 4.5.

Figure 4-3 depicts the possible options of electricity trade, which cannot be modelled using physical electricity flow data at interconnectors.

[2] A corporate GHG accounting and reporting standard

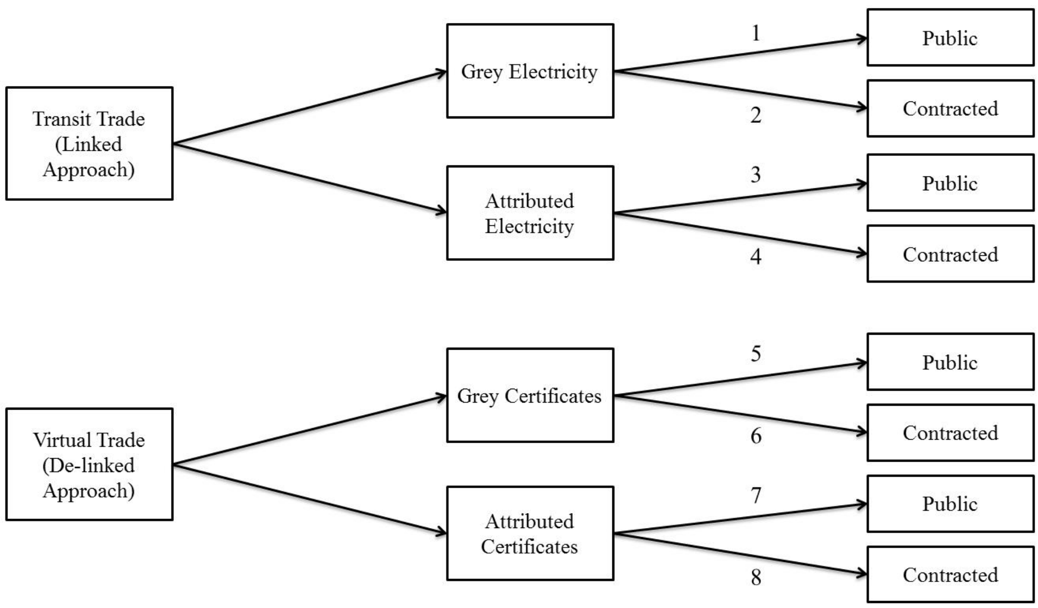

Figure 4-3: Trade Schemes of Electricity

The basic differentiation lies here, once more, between the physical trade and the virtual trade. Again, both options can be traded either as grey or as attributed. In this context, grey means that the exact origin of the traded electricity is unknown. Therefore, the attribute of grey electricity generally corresponds with the production mix of the originating country. The exact origin for attributed electricity trade, on the other hand, is known and can be directly attributed with an emission factor of e.g. 0.007 kg CO_2-e/ kWh in case of electricity produced from wind turbines. The trade options are explained in more detail below:

Option 1: The transit of physical grey electricity (e.g. from the electricity stock exchange) which is fed into the public grid.

Option 2: The transit of physical grey electricity that is delivered directly to a specific consumer and is therefore not available to the public.

Option 3: The transit of physical attributed electricity from an electricity supplier, which is fed into the public grid.

Option 4: The transit of physical attributed electricity from an electricity supplier, which is delivered directly to a specific consumer and is therefore not available to the public.

Option 5: The purchase of grey electricity certificates from an electricity supplier that are available for the public market.

Option 6: The purchase of grey electricity certificates which are allocated directly to the specific consumer and are therefore not available to the public.

Option 7: The purchase of attributed electricity certificates from an electricity supplier available to the public (e.g. in order to reach national goals on the share of renewables in electricity generation as described in the Renewable Energy Directive (European Commission 2009).

Option 8: The purchase of attributed certificates for a specific consumer, which are not available to the public.

Currently, very few data on the corresponding amounts traded through these eight options is available. These trade schemes, like certificate trade, bear a high risk of double counting in case already accounted volumes of grey or attributed electricity are not subtracted from the national inventory. Therefore, the European Union is planning to establish a system accounting for the quantities and qualities of electricity certificates traded within Europe (TIMPE, C. 2007) by setting up rules on the issuance of certificates.

The problem can only be solved by calculating and using national residual mixes, where the attributed electricity volumes already accounted for, are excluded. In this case, a residual mix is defined by the mix that a consumer that is not contracted to a specific supplier dissipates in a specific region. This approach is very common in LCA in order to estimate the impact of electricity consumption on a product or a service when the electricity supplier is unknown. In this case, the electricity consumed is an average regional mix.

Within the E-Track project and the RE-DISS project (which have been partly funded by the European Commission), a method for the calculation of this residual mix and for the general tracking of electricity is developed (TIMPE, C. 2007). The purpose is to provide more transparency and information to customers (DRAECK, M. et al. 2009) and LCA practitioners. The RE-DISS project applies this method developed by E-Track and gathers data in order to calculate national residual mixes. The data is still not detailed enough to be used for LCA purposes (European Platform Electricity Disclosure 2010) but the follow up project RE-DISS II is on its way and could possibly provide LCA Data.

The EMM is therefore structured to use the DIMENSION Model (EWI 2011) data as a basis. If data on either transit trade and/or certificate trade is available, it can be entered and analysed additionally. Figure 4-4 shows the basic structure of the EMM and the trade modules.

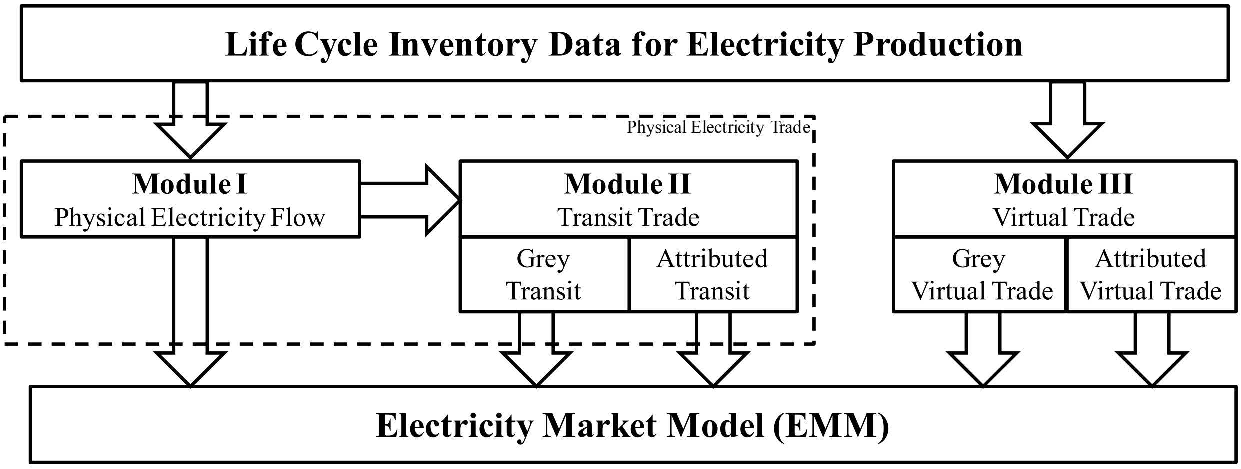

Figure 4-4: Modules of the EMM

The Modules of the EMM are summarised below:

- **Module I** (see Chapter 4.3) describes the physical electricity flow between the countries. Data is provided by the DIMENSION Model or interconnector data, respectively.
- **Module II** describes the transitioning flows (electricity flows through a region/country as well as the transiting directly to a consumer). Transit flows can be either grey (electricity consumption mix of the exporting country) or attributed (e.g. green electricity).
- **Module III** describes the virtual trade of electricity (trade of electricity without physical delivery). The virtual trade can be grey (electricity consumption mix of the exporting country) or attributed (e.g. green electricity).

If no data for Module II or Module III is available so far, they are accounted as “0” and the DIMENSION Model (EWI 2011) data or interconnector data is used. As soon as a European data basis as described in the Re-Diss II project (European Commission 2012) is available, this data can then be added to the EMM. For this dissertation, a case study for countries where data of high quality is available is conducted for each Module II and Module III.

4.2.2 Timing of Electricity Trade

The timing of electricity trade also requires consideration when assessing a high-resolution electricity system. There are two options when purchasing electricity or certificates:

Isochronous feed-in: If the electricity is fed-in isochronously to the consumption of the electricity, it is called "isochronous feed-in". These products are offered by (Greenpeace Energy 2013) or TÜV Süd quality label EE02 (TÜV Süd 2010). For the EMM it means that the correction through Module II and/or Module III has to be performed in a high time-resolution. This requires the knowledge of the load curve of the consumer as described in e.g. (HESSELBACH, J. et al. 2012), which is generally estimated by using typical load curves (Greenpeace Energy 2013).

Non-isochronous feed-in: If the electricity/certificate supplier feeds-in exactly the amount of electricity (certificates) his customer consumes over the period of one year it is called "non-isochronous feed-in". In case of certificates, the number that has to be issued is determined by meter readings. Such a meter reading must take place at least at the end of each calendar year. This means that certificates for electricity volumes produced in January of year X must be issued in December of year X at the latest. Cancellation takes place after selling certificates to the end consumer, but 12 months after issuance at the latest. The certificates expire after 12 months. The feed-in time does not affect the point in time, when certificates/GOs are cancelled since their cancellation takes place when sold to the end consumer. Thus, the non-isochronous feed-in of electricity can be implemented into the EMM on an annual basis.

Accounting emissions of electricity consumption is difficult for several reasons: Electricity is immaterial and difficult to trace back, data on traded volumes are currently not available and consistent and detailed regulations are missing. A system for tracking electricity attributes is in the making and will facilitate to keep an overview on physical and traded electricity volumes. Until the tracking system is finished, only physical electricity flows can be accounted for (Module I). Nevertheless, Module II and Module III are implemented into the EMM in order to include data promptly once available.

4.3 Module I - Physical Electricity Flow and the Leontief Matrix

Eurostat (Eurostat 2013) publishes data on the physical electricity flow between different regions on a regular basis. These physical electricity flows can be measured at the interconnector. Figure 4-5 depicts the physical electricity trade in Europe for the year 2009 (Eurostat 2013).

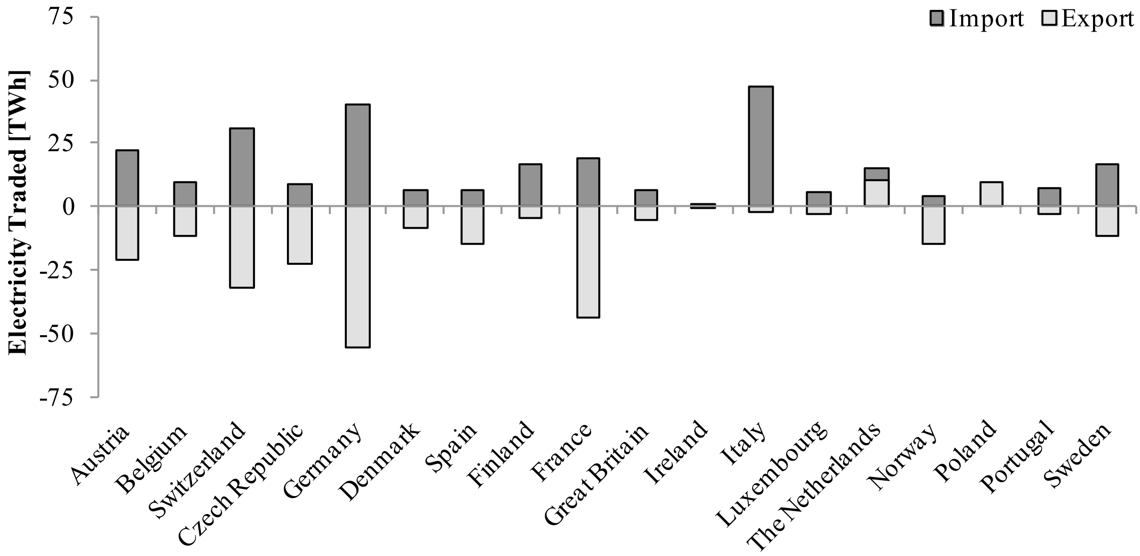

Figure 4-5: Physical Electricity Trade in Europe 2009 (Eurostat 2013)

The amount of electricity traded between different regions depends on various factors such as demand, costs of electricity production or weather conditions. As previously mentioned, the DIMENSION Model (EWI 2011) is able to simulate the electricity exchange at an hourly time resolution depending on these factors. Modelling electricity trade of such a complex system as that of the European grid involves the management of a vast amount of data, especially when aiming at a high time resolution. A correct and efficient data handling is therefore crucial for an effective model analysis. Thus, this section introduces a methodology to address the issue of data handling in the EMM. The basic idea is to develop an automated calculation procedure of processing high-resolution trade data. In order to explain the calculation procedure a simplified fictive example of a trade system between several regions at a time t = 0 as depicted in Figure 4-6 is analysed.

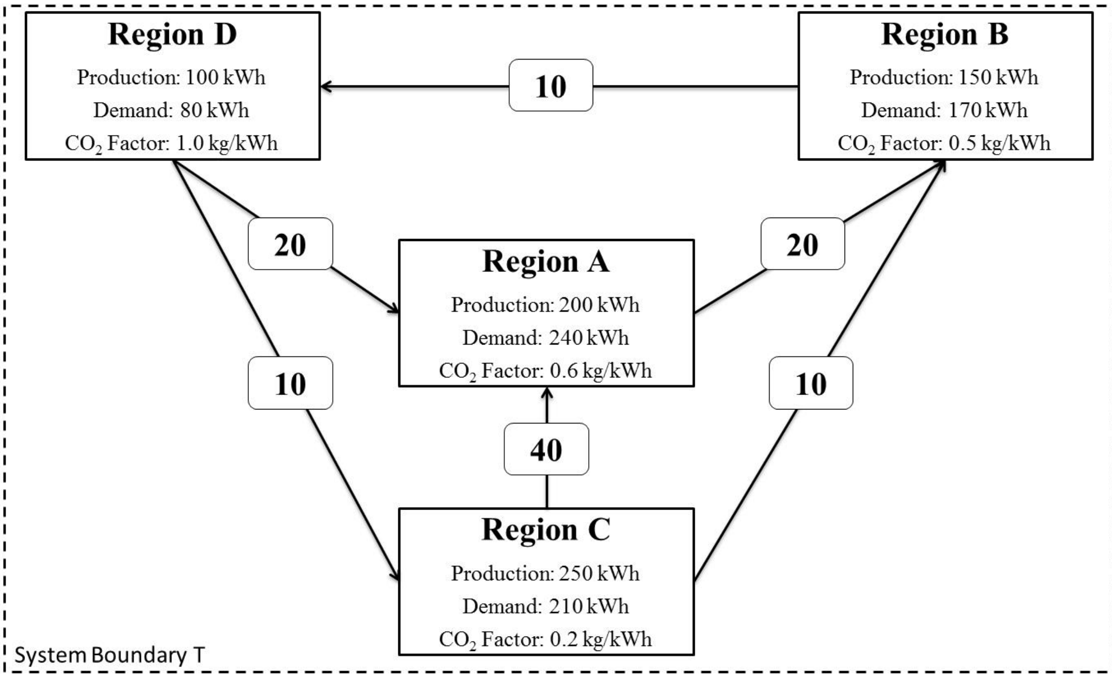

Figure 4-6: Electricity Market System (Example 1)

This example represents an enclosed electricity system. No other trade partners than Region A to D are involved. Secondly, there are no trade contracts without physical delivery and no transit trades as each region purchases physical electricity from neighbouring countries. Each region produces a certain amount of electricity (e.g. Region A produces 200 kWh) with a certain attribute (e.g. Region A produces electricity with 1.0 kg CO_2/kWh) and consumes a certain amount of electricity (e.g. Region A consumes 180 kWh). In order to balance production and demand the four regions are trade (Region A delivers 10 kWh to Region C and 20 kWh to Region A; Region A imports 20 kWh from Region D etc.). Eventually all regions can balance production and demand. This is a realistic assumption, as the European grid cannot store electricity. Hence, the production and demand of each participating region must be balanced.

The production, consumption and the trade relations of the regions in Figure 4-6 can be described as shown in Table 4-4.

Table 4-4: Trade Table

From → To↓	**A**	**B**	**C**	**D**	**∑ = Consumption**
A	180	0	40	20	**240**
B	20	140	10	0	**170**
C	0	0	200	10	**210**
D	0	10	0	70	**80**
∑ = Production	**200**	**150**	**250**	**100**	

Region A produces 200 kWh and exports to Region B 10 kWh. Accordingly, the trade A →B is 20 kWh and the trade B →C is 20 kWh, respectively. The main diagonal represents the domestic production consumed in the home market, the total production of each region is the sum of the columns and the demand is the sum of lines. It is important to note that Table 4-4 only shows imports as positive values. Exports are shown in the lines e.g. Region A imports 20 kWh from Region C and 10 kWh from Region D as shown in line one. This small market can be modelled using a matrix calculation. Thus, Table 4-4 can be translated into the following "Trade Matrix" **T**:

$$T = \begin{bmatrix} 180 & 0 & 40 & 20 \\ 20 & 140 & 10 & 0 \\ 0 & 0 & 200 & 10 \\ 0 & 10 & 0 & 70 \end{bmatrix} \qquad \textbf{Trade-Matrix}$$

Furthermore, the "Production-Vector" $\vec{\boldsymbol{p}}$ as the sum of the columns and the "Consumption-Vector" $\vec{\boldsymbol{c}}$ as the sum of the lines can be defined:

$$\vec{p} = \begin{bmatrix} 200 \\ 150 \\ 250 \\ 100 \end{bmatrix}$$ **Production-Vector**

$$\vec{c} = \begin{bmatrix} 240 \\ 170 \\ 210 \\ 80 \end{bmatrix}$$ **Consumption-Vector**

The production of each region is associated with CO_2 emissions produced per kWh. Therefore, analogue to the "Production-Vector" $\vec{\boldsymbol{p}}$ and "Consumption-Vector" $\vec{\boldsymbol{c}}$ a vector of specific CO_2 emissions can be defined as the "Relative Production-Emission-Vector" $\vec{\boldsymbol{p}}_{\boldsymbol{rel}}^{\boldsymbol{e}}$:

$$\vec{p}_{rel}^{e} = \begin{bmatrix} 0.6 \\ 0.5 \\ 0.2 \\ 1.0 \end{bmatrix}$$ **Relative Production-Emission-Vector**

The multiplication of the "Trade-Matrix" **T** and the "Relative Production-Emission-Vector" $\vec{\boldsymbol{p}}_{\boldsymbol{rel}}^{\boldsymbol{e}}$ delivers the "Consumption-Emission-Vector" $\vec{\boldsymbol{c}}^{\boldsymbol{e}}$ showing the total CO_2 emissions for each region including CO_2 emissions from own production and imports excluding exported CO_2 emissions.

$$\vec{c}^{e} = T \cdot \vec{p}_{rel}^{e} = \begin{bmatrix} 180 & 0 & 40 & 20 \\ 20 & 140 & 10 & 0 \\ 0 & 0 & 200 & 10 \\ 0 & 10 & 0 & 70 \end{bmatrix} \cdot \begin{bmatrix} 0.6 \\ 0.5 \\ 0.2 \\ 1.0 \end{bmatrix} = \begin{bmatrix} 136 \\ 84 \\ 50 \\ 75 \end{bmatrix}$$

Consumption-Emission-Vector

Now the "Relative Consumption-Emission-Vector" $\vec{\boldsymbol{c}}_{\boldsymbol{rel}}^{\boldsymbol{e}}$ can be computed as follows:

$$\vec{c}^{e}_{rel} = Diag(\vec{c})^{-1} \cdot \vec{c}^{e} = \begin{bmatrix} 240 & 0 & 0 & 0 \\ 0 & 170 & 0 & 0 \\ 0 & 0 & 210 & 0 \\ 0 & 0 & 0 & 80 \end{bmatrix}^{-1} \cdot \begin{bmatrix} 136 \\ 84 \\ 50 \\ 75 \end{bmatrix} = \begin{bmatrix} 0.567 \\ 0.494 \\ 0.238 \\ 0.938 \end{bmatrix}$$

Relative Consumption-Emission-Vector

The procedure described above can be summarised with the following equation:

$$\vec{c}^{e}_{rel} = Diag(\vec{c})^{-1} \cdot T \cdot \vec{p}^{e}_{rel}$$

Figure 4-7 visualises the differences between the CO_2 emissions of the production mix and the consumption mix.

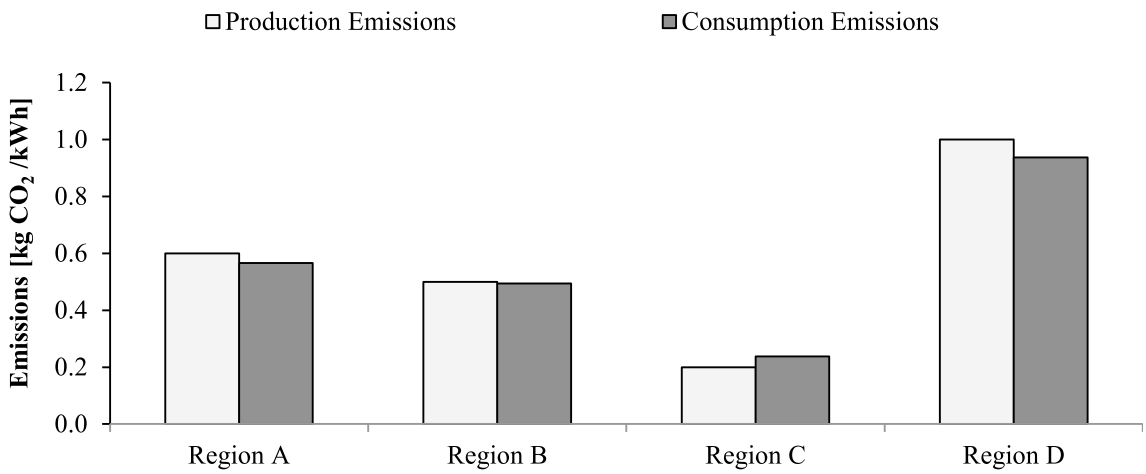

Figure 4-7: Production Emissions vs. Consumption Emissions

In this example, the differences are around 20% for Region C. Depending on the intensity of trade and the emission factors of the traded electricity, the electricity production and electricity consumption emissions can vary significantly. Trade is therefore of vital importance for the LCA of electricity.

The procedure evaluated above rests upon the Leontief Matrix developed for input-output models in economics (LEONTIEF, W. 1970), (LEONTIEF, W. 1970) developed by the 1973 Nobel Prize winner Wassily Leontief (1905 – 1999). Since electricity exchange can be described as a specific type of input-output economics, the study at hand uses a slight adaption of the

Leontief Matrix. Instead of using monetary units, different parties exchange emission units. First attempts to combine the LCA approach with economic input-output (EIO) models can be found in (HENDRICKSON, C. T. et al 1998). Many studies followed, forming a new methodological approach called EIO-LCA where non-economic data such as environmental burdens are processed (COSTELLO, C. et al. 2011), (HAWKINS, T. et al 2007), (HENDRICKSON, C. T. et al 1998), (HUANG, Y. A. et al 2009), (MATTHEWS, H. S. et al. 2000) and (MUELLER, B. 2011). EIO-LCA is most commonly applied to analyse whole industry sectors. There is, however, no work of EIO-LCA known so far to cover the electricity sector. The advantage of this approach lies in its provision of an analytical framework for the impact of electricity trade between countries without using rough assumptions regarding transit trade. Unlike the current trade models described in Chapter 2 this approach is designed to assess the impact of transit trade in a second calculation step by defining Module II. The EIO-LCA is a scientifically proven and robust way to assess the impact of trade between market participants in a balanced market system. Additionally, an automated and continuous handling of the vast amount of data is possible using this mathematical description of electricity exchange.

There are more options for a further analysis using a modified Leontief-Matrix. The emission trade through the electricity grid can be quantified by creating additional matrixes and vectors. For the "Relative Production-Emission-Matrix" $\mathbf{P}^{\mathbf{e}}_{\mathbf{rel}}$ the "Relative Production-Emission-Vector" $\vec{\boldsymbol{p}}^{\boldsymbol{e}}_{\boldsymbol{rel}}$ represents the main diagonal:

$$\mathrm{P}^{\mathrm{e}}_{\mathrm{rel}} = \mathrm{Diag}(\vec{p}^{e}_{rel}) = \begin{bmatrix} 0.6 & 0 & 0 & 0 \\ 0 & 0.5 & 0 & 0 \\ 0 & 0 & 0.2 & 0 \\ 0 & 0 & 0 & 1.0 \end{bmatrix}$$ **Relative Production-Emission-Matrix**

By multiplying the "Trade-Matrix" $\mathbf{T}$ with the "Relative Production-Emission-Matrix" $\mathbf{P}^{\mathbf{e}}_{\mathbf{rel}}$ the CO_2 trade pattern can be visualised as "Emission-Trade-Matrix" $\mathbf{T}^{\mathbf{e}}$:

$$T \cdot \mathrm{P}_{\mathrm{rel}}^{\mathrm{e}} = T^e = \begin{bmatrix} 180 & 0 & 40 & 20 \\ 20 & 140 & 10 & 0 \\ 0 & 0 & 200 & 10 \\ 0 & 10 & 0 & 70 \end{bmatrix} \cdot \begin{bmatrix} 0.6 & 0 & 0 & 0 \\ 0 & 0.5 & 0 & 0 \\ 0 & 0 & 0.2 & 0 \\ 0 & 0 & 0 & 1.0 \end{bmatrix} = \underbrace{\begin{bmatrix} 108 & 0 & 8 & 20 \\ 12 & 70 & 2 & 0 \\ 0 & 0 & 40 & 10 \\ 0 & 5 & 0 & 70 \end{bmatrix}}_{\textbf{Emission-Trade-Matrix}}$$

Using the "Emission-Trade-Matrix" $\mathbf{T^e}$, the amounts of CO_2 traded can be determined for each region. Region A, for instance, imports 8 kg CO_2 from Region C and 20 kg CO_2 from Region C. The exports of 12 kg CO_2 are going to Region B whereas 108 kg CO_2 of internally produced CO_2 emissions remain within Region A.

The "Emission-Trade-Matrix" $\mathbf{T^e}$ is displayed in Table 4-5 as follows:

Table 4-5: CO_2 Trade Table

From → **To↓**	**A**	**B**	**C**	**D**	**∑= Consumption CO_2**
A	108	0	8	20	**136**
B	12	70	2	0	**84**
C	0	0	40	10	**50**
D	0	5	0	70	**75**
∑= Production CO_2	**120**	**75**	**50**	**100**	

The sum of the columns represents the amount of CO_2 produced in each region and the sum of the lines represents the amount of CO_2 consumed in each region. These sums can be represented as vectors. For emissions produced in each country the "Emission-Production-Vector" $\vec{\boldsymbol{p}}^{\boldsymbol{e}}$ and for emissions consumed in each region the "Consumption-Emission-Vector" $\vec{\boldsymbol{c}}^{\boldsymbol{e}}$ can be quantified:

$$\vec{p}^e = \begin{bmatrix} 120 \\ 75 \\ 50 \\ 100 \end{bmatrix} \qquad \vec{c}^e = \begin{bmatrix} 136 \\ 84 \\ 50 \\ 75 \end{bmatrix}$$

This procedure provides a good overview of imported and exported CO_2 emissions. The amount of emission imports can be computed as follows:

$$\vec{\iota}^e = \vec{c}^e - \vec{p}^e = \begin{bmatrix} 136 \\ 84 \\ 50 \\ 75 \end{bmatrix} - \begin{bmatrix} 120 \\ 75 \\ 50 \\ 100 \end{bmatrix} = \begin{bmatrix} 16.0 \\ 9 \\ 0 \\ -25 \end{bmatrix} \qquad \textbf{Imported Emission-Vector}$$

According to $\vec{\boldsymbol{\iota}}^{\boldsymbol{e}}$, Region A and Region B import emissions, whereas Region D exports emissions. The sum of all components of $\vec{\boldsymbol{\iota}}^{\boldsymbol{e}}$ must be zero as the system is enclosed. This calculation is important to account for Scope 2 emissions of e.g. the GHG protocol (RANGANATHAN, J. et al 2004) for different regions.

Module I accounts for direct trade only. The following chapter describes the consideration of transit trade using Module II.

4.4 Module II - Transit Flows

Transit flows constitute a significant problem within the LCA of a complex electricity system (MÉNARD, M. et al. 1998). As previously described, this problem occurs if a country/region purchases electricity from a non-neighbouring country/region that is then delivered via the grid of a third party. The physical model (Module I) has therefore to be corrected for transit flows as the third party country is not consuming the electricity at all. As described in Chapter 4.2, transit flows can be either grey or “attributed”.

4.4.1 Grey Transit Flows

Grey electricity is an expression for electricity of unknown origin regarding the type of power plants having produced the electricity (Deutscher Bundestag 2005). Grey electricity can, for instance, be purchased at the energy stock exchange (European Energy Exchange (EEX) 2013). Grey electricity can either be fed into the public grid or consumed directly by a customer. The following chapters describe how to handle public and customer specific grey electricity, respectively.

4.4.1.1 Public Grey Transit Flows

Figure 4-8 depicts a fictive example of transit trade of grey electricity through two countries.

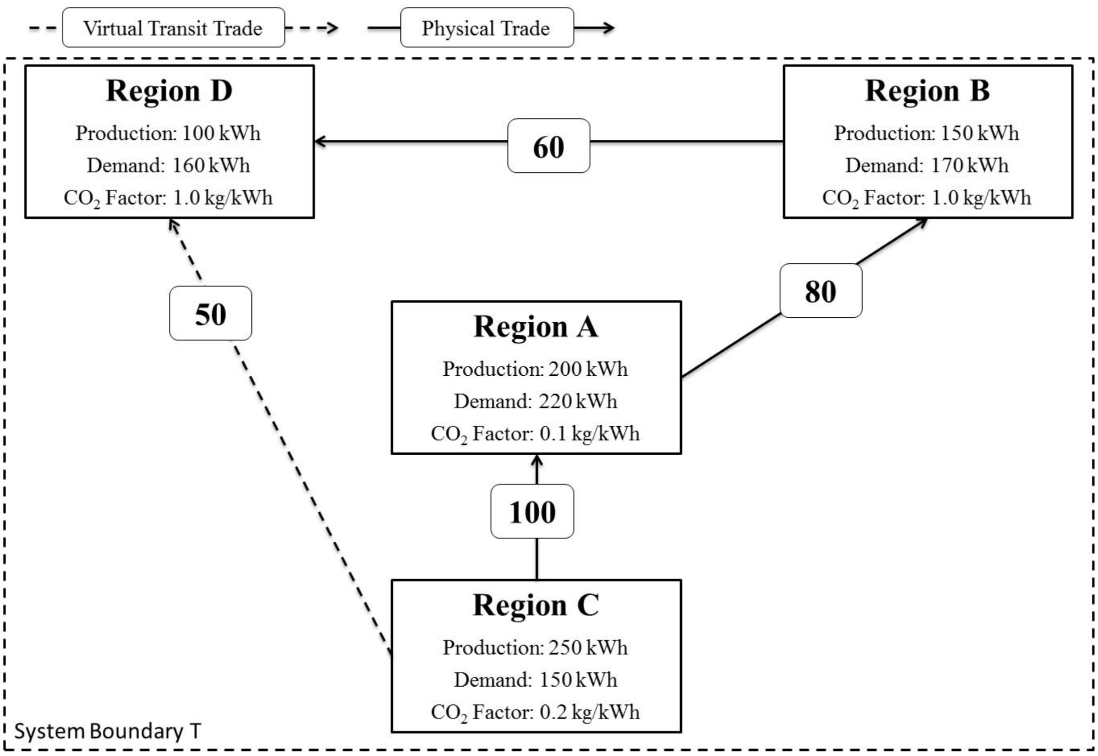

Figure 4-8: Electricity Market System with Transit of Grey Electricity (Example 2)

Region C is committed to deliver 50 kWh to Region D using the electricity grid of Region A and Region B. A "Trade-Matrix" **T** (which is not accounting for transit flows), the "Production-Vector" $\vec{\boldsymbol{p}}$, the "Relative Production-Vector" $\vec{\boldsymbol{p}}^{\boldsymbol{e}}_{\boldsymbol{rel}}$ and the "Consumption-Vector" $\vec{\boldsymbol{c}}$ are therefore defined as follows:

$$T = \begin{bmatrix} 120 & 0 & 100 & 0 \\ 80 & 90 & 0 & 0 \\ 0 & 0 & 150 & 0 \\ 0 & 60 & 0 & 100 \end{bmatrix} \qquad \vec{p} = \begin{bmatrix} 200 \\ 150 \\ 250 \\ 100 \end{bmatrix}$$

$$\vec{p}_{rel}^{e} = \begin{bmatrix} 0.1 \\ 1.0 \\ 0.2 \\ 1.0 \end{bmatrix} \qquad \vec{c} = \begin{bmatrix} 220 \\ 170 \\ 150 \\ 160 \end{bmatrix}$$

The total carbon balance can be computed using the "Production-Vector" $\vec{\boldsymbol{p}}$ and the "Relative Production-Emission-Vector" $\vec{\boldsymbol{p}}_{\boldsymbol{rel}}^{\boldsymbol{e}}$:

$$\vec{p}_{rel}^{e\ T} \cdot \vec{p} = \begin{bmatrix} 0.1 \\ 1.0 \\ 0.2 \\ 1.0 \end{bmatrix}^T \cdot \begin{bmatrix} 200 \\ 150 \\ 250 \\ 100 \end{bmatrix} = 320 \text{ kg}$$

The total CO_2 emissions of the system amount to 320 kg. In order to correct the system from transit flows these must be subtracted from the physical electricity flows. In addition to the correction of the flows, a virtual trade flow is introduced indicating the direct electricity delivery as depicted in Figure 4-9.

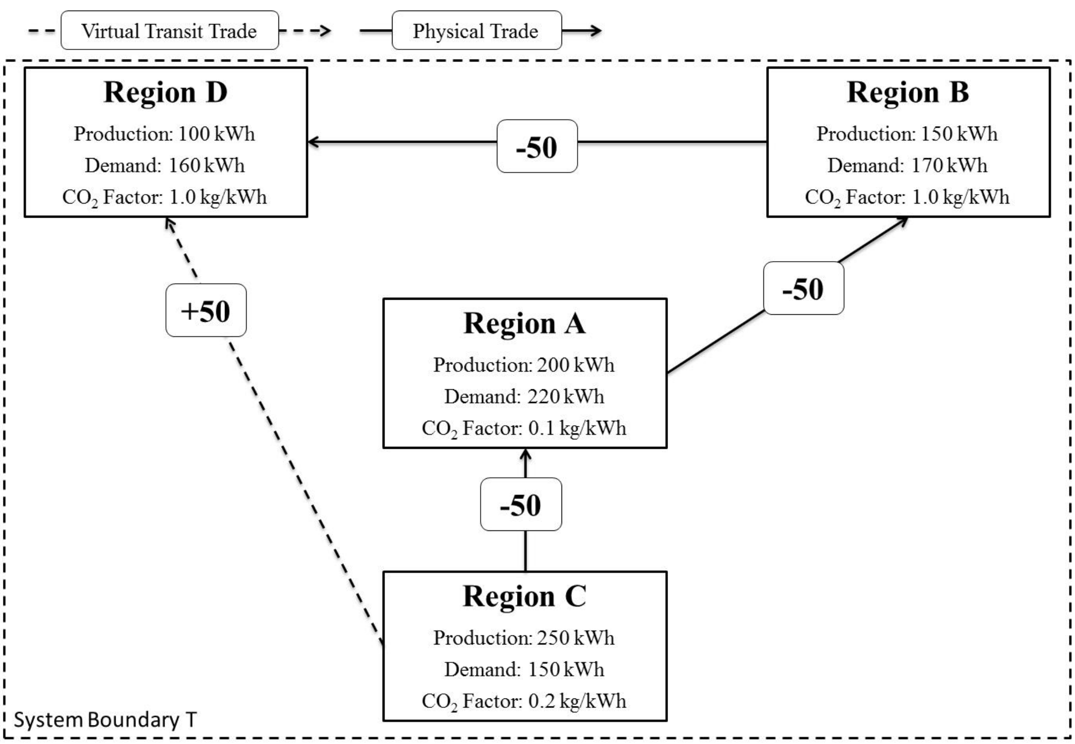

Figure 4-9: Transit-Correction

Based on this relation the following "Transit-Correction-Matrix" ${}^{\mathbf{T}}_{\mathbf{C}}\mathbf{T}$ can be created:

$$
{}^{T}_{C}T \ = \begin{bmatrix} 50 & 0 & -50 & 0 \\ -50 & 50 & 0 & 0 \\ 0 & 0 & 50 & 0 \\ 0 & -50 & 0 & 0 \end{bmatrix}
$$

This "Transit-Correction-Matrix" ${}^{\mathbf{T}}_{\mathbf{C}}\mathbf{T}$ is designed as an extension module for the EMM in order to account for transit trade, if data is available. Adding the "Trade-Matrix" T and the "Transit-Correction-Matrix" ${}^{\mathbf{T}}_{\mathbf{C}}\mathbf{T}$ delivers the "Final Trade-Matrix" $\breve{\mathrm{T}}$:

$$
\begin{aligned}
\breve{T} = T + {}^{T}_{C}T &= \begin{bmatrix} 120 & 0 & 100 & 0 \\ 80 & 90 & 0 & 0 \\ 0 & 0 & 150 & 0 \\ 0 & 60 & 0 & 100 \end{bmatrix} + \begin{bmatrix} 50 & 0 & -50 & 0 \\ -50 & 50 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & -50 & 50 & 0 \end{bmatrix} \\
&= \begin{bmatrix} 170 & 0 & 50 & 0 \\ 30 & 140 & 0 & 0 \\ 0 & 0 & 150 & 0 \\ 0 & 10 & 50 & 100 \end{bmatrix}
\end{aligned}
$$

The "Final Trade Matrix" $\breve{\boldsymbol{T}}$ can be visualised as shown in Figure 4-10**:**

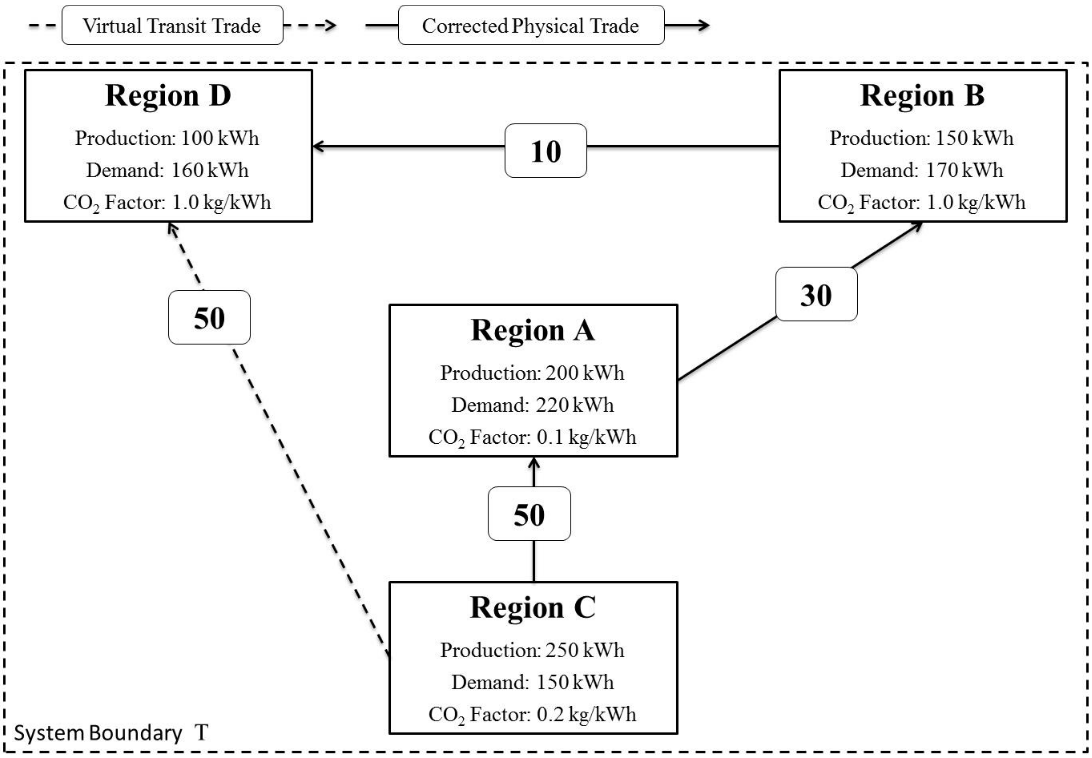

Figure 4-10: Final Trade

Using the "Final Trade-Matrix" $\breve{\mathbf{T}}$ and "Relative Production-Emission-Vector" $\vec{\boldsymbol{p}}^{\boldsymbol{e}}_{\boldsymbol{rel}}$, the "Corrected Consumption-Emission-Vector" $\vec{\boldsymbol{c}}^{\boldsymbol{e}}$ can be created:

$$\vec{c}^e = \breve{T} \cdot \vec{p}^e_{rel} = \begin{bmatrix} 170 & 0 & 50 & 0 \\ 30 & 140 & 0 & 0 \\ 0 & 0 & 200 & 0 \\ 0 & 10 & 0 & 100 \end{bmatrix} \cdot \begin{bmatrix} 0.1 \\ 1.0 \\ 0.2 \\ 1.0 \end{bmatrix} = \begin{bmatrix} 27 \\ 143 \\ 30 \\ 120 \end{bmatrix}$$

Now the "Corrected Relative Consumption-Emission-Vector" $\vec{\boldsymbol{c}}^{\boldsymbol{e}}_{\boldsymbol{rel}}$ can be computed as follows:

$$\vec{c}^e_{rel} = Diag(\vec{c})^{-1} \cdot \vec{c}^e = \begin{bmatrix} 220 & 0 & 0 & 0 \\ 0 & 170 & 0 & 0 \\ 0 & 0 & 150 & 0 \\ 0 & 0 & 0 & 160 \end{bmatrix}^{-1} \cdot \begin{bmatrix} 27 \\ 143 \\ 30 \\ 120 \end{bmatrix} = \begin{bmatrix} 0.123 \\ 0.841 \\ 0.200 \\ 0.750 \end{bmatrix}$$

Figure 4-11 depicts the difference between the consumption emissions with and without using Module II for correcting the transit flows. Transit flows are not consumed in the transiting country. Hence, the relative consumption emissions with the consideration of transit flows is the most appropriate approach to be used for an environmental assessment of electricity consumption.

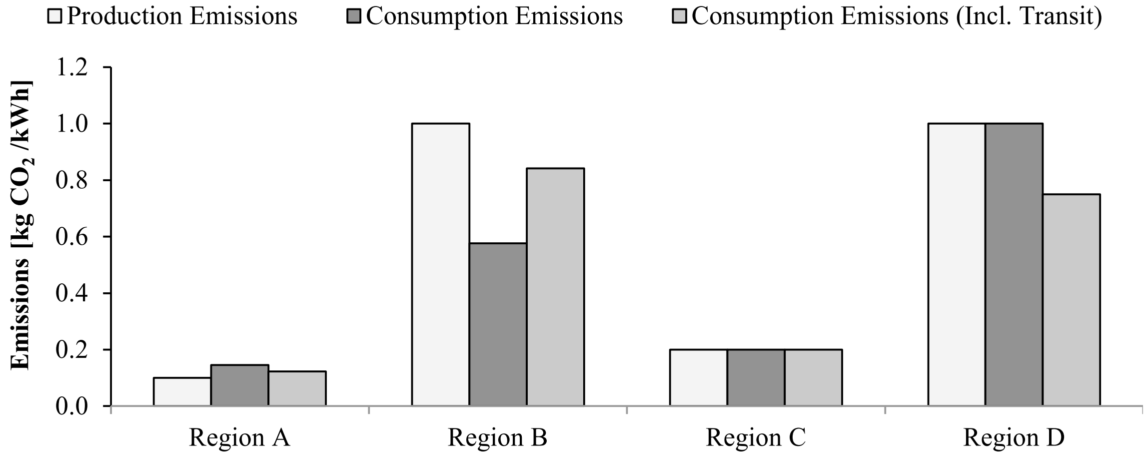

Figure 4-11: Production Emissions vs. Consumption Emissions with and without Transit of Grey Electricity

The relative consumption emissions can differ significantly when accounting for transit flows as the emissions are now directly transferred from Region C to Region D. Hence, the electricity consumption emissions of Region D decrease significantly compared to the care when transit trade is not accounted for. As a result, the emission imports of each region, including the transit flows, can be computed as follows:

$$\vec{\iota}^{e} = \vec{c}^{e} - \vec{p}^{e} = \begin{bmatrix} 27 \\ 143 \\ 30 \\ 120 \end{bmatrix} - \begin{bmatrix} 20 \\ 150 \\ 50 \\ 100 \end{bmatrix} = \begin{bmatrix} 7 \\ -7 \\ -20 \\ 20 \end{bmatrix}$$

The positive components of $\vec{\boldsymbol{\iota}}^{\boldsymbol{e}}$ specify that Region A and Region D import indirect emissions. Negative values indicate an export of indirect emissions as for Region B and Region C. Again, the sum of all components of $\vec{\boldsymbol{\iota}}^{\boldsymbol{e}}$ must be zero as the system is enclosed.

4.4.1.2 Contracted Grey Transit Flows

The example above assumes that the grey electricity bought into Region D is fed into the public grid. In some cases, however, the grey electricity is "owned" by the final customer and is therefore not available for the public market. Since the consumption emission calculation of this study aims to assess the public market and not a specific customer, this has to be corrected through altering. The "Consumption-Vector" $\vec{\boldsymbol{c}}$ is corrected by the amount of electricity already sold to a specific customer using the "Contract-Trade-Vector" $^{c}\vec{\boldsymbol{t}}$.

$$^{c}\vec{t} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 50 \end{bmatrix}$$ **Contract-Trade-Vector**

$$\vec{\acute{c}} = \vec{c} - {}^{c}\vec{t} = \begin{bmatrix} 220 \\ 170 \\ 150 \\ 160 \end{bmatrix} - \begin{bmatrix} 0 \\ 0 \\ 0 \\ 50 \end{bmatrix} = \begin{bmatrix} 220 \\ 170 \\ 150 \\ 110 \end{bmatrix}$$ **Corrected Consumption-Vector**

Furthermore, the "Consumption-Emission-Vector" $\vec{\boldsymbol{c}}^{\boldsymbol{e}}$ of the previous example has to be corrected by the amount of emissions generated by contracted grey electricity. This is done by computing the amount of CO_2 that is directly traded to a consumer. The attributes of the contracted electricity are defined by the "Relative-Contract-Trade-Vector" $^{c}\vec{\mathbf{t}}_{\boldsymbol{rel}}$

$$^{c}\vec{\mathrm{t}}_{rel} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0.2 \end{bmatrix}$$ **Relative Contract-Trade-Vector**

Now the "Corrected Consumption-Emission-Vector" $\vec{\acute{\boldsymbol{c}}}^{\boldsymbol{e}}$ can be computed:

$$\vec{c}^e = \vec{c}^e - Diag\left({}^{c}\vec{t}_{rel}\right) \cdot \ {}^{c}\vec{t} = \begin{bmatrix} 27 \\ 143 \\ 30 \\ 120 \end{bmatrix} - \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.2 \end{bmatrix} \cdot \begin{bmatrix} 0 \\ 0 \\ 0 \\ 50 \end{bmatrix} = \begin{bmatrix} 27 \\ 143 \\ 30 \\ 110 \end{bmatrix}$$

Corrected Consumption-Emission-Vector

Now the "Corrected Relative Consumption-Emission-Vector" $\vec{\boldsymbol{c}}^{\boldsymbol{e}}_{\boldsymbol{rel}}$ can be computed.

$$\vec{c}^e_{rel} = Diag\left(\vec{c}\right)^{-1} \cdot \ \vec{c}^e = \begin{bmatrix} 220 & 0 & 0 & 0 \\ 0 & 170 & 0 & 0 \\ 0 & 0 & 150 & 0 \\ 0 & 0 & 0 & 110 \end{bmatrix}^{-1} \cdot \ \begin{bmatrix} 27 \\ 143 \\ 30 \\ 110 \end{bmatrix} = \begin{bmatrix} 0123 \\ 0.841 \\ 0.200 \\ 1.000 \end{bmatrix}$$

Corrected Relative Consumption-Emission-Vector

None of the grey electricity Region D purchased from Region C is available for the public market as it is contracted for a specific consumer. As a result, the emissions of the consumption mix for Region D remain at 1.0 kg CO_2/ kWh.

The procedure described in Chapter 4.4.1 can be summarised using the following equation:

$$\vec{c}^e_{rel} = Diag\left(\vec{c} - \ {}^{c}\vec{t}\right)^{-1} \cdot \left[(T + {}^{T}_{C}T) \ \cdot \vec{p}^e_{rel} - \ (Diag\left(\overrightarrow{{}^{c}t}\right) \cdot \left(Diag(\vec{c})^{-1} \ \cdot \ (T + {}^{T}_{C}T)\right) \cdot \ \vec{p}^e_{rel}\right]$$

Where the term:

$\boldsymbol{Diag(\vec{c} - \ {}^{c}\vec{t})^{-1}}$	represents the consumption term corrected by contracted electricity
$(\boldsymbol{T} + {}^{\boldsymbol{T}}_{\boldsymbol{C}}\boldsymbol{T})$	represents the trade relations corrected by transit flows
$\vec{\boldsymbol{p}}^{\boldsymbol{e}}_{\boldsymbol{rel}}$	represents the production properties

$$\mathbf{Diag}\left({}^{c}\vec{\boldsymbol{t}} \right) \cdot \left(\mathbf{Diag}(\vec{\boldsymbol{c}})^{-1} \cdot \left(\mathbf{T} + {}^{\mathbf{T}}_{\mathbf{C}}\mathbf{T} \right) \right) \cdot \vec{\boldsymbol{p}}^{\boldsymbol{e}}_{\boldsymbol{rel}}$$

represents the directly contracted consumption emissions, which are removed from the public market.

4.4.2 Attributed Transit Flows

In Chapter 4.4.1 only grey electricity is traded. It is, however, very common to purchase attributed electricity (e.g. generally green electricity) from non-neighbouring countries. When a physical delivery has been agreed on, the electricity must be passed via transiting countries.

4.4.2.1 Public Attributed Transit Flows

The general procedure is as described in Chapter 4.4.1. The visualisation of the trade relation is as depicted in Figure 4-12.

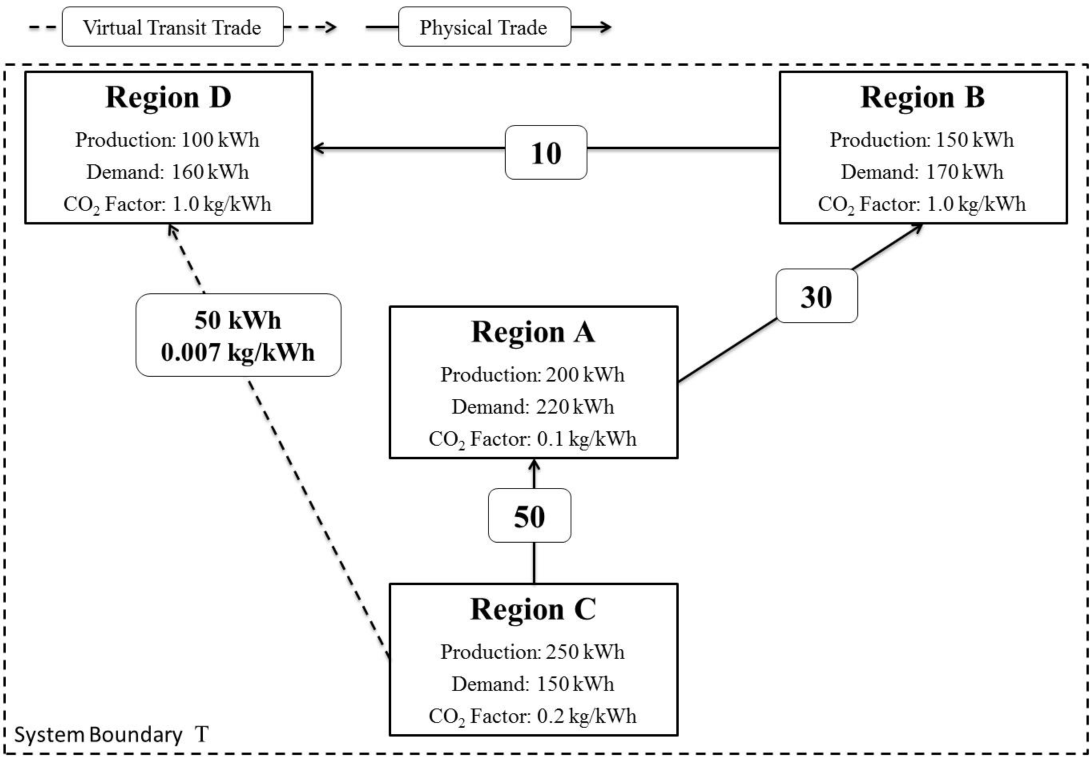

Figure 4-12: Electricity Market System with Transit of Attributed Electricity (Example 3)

A "Trade-Matrix" **T** (which is not accounting for transit flows), the "Production-Vector" $\vec{\boldsymbol{p}}$, the "Relative Production-Emission-Vector" $\vec{\boldsymbol{p}}^{\boldsymbol{e}}_{\boldsymbol{rel}}$ and the "Consumption-Vector" $\vec{\boldsymbol{c}}$ are defined as follows:

$$T = \begin{bmatrix} 120 & 0 & 100 & 0 \\ 80 & 90 & 0 & 0 \\ 0 & 0 & 150 & 0 \\ 0 & 60 & 0 & 100 \end{bmatrix} \qquad \vec{p} = \begin{bmatrix} 200 \\ 150 \\ 250 \\ 100 \end{bmatrix}$$

$$\vec{p}^{e}_{rel} = \begin{bmatrix} 0.1 \\ 1.0 \\ 0.2 \\ 1.0 \end{bmatrix} \qquad \vec{c} = \begin{bmatrix} 220 \\ 170 \\ 150 \\ 160 \end{bmatrix}$$

The total carbon balance can be computed as follows:

$$\vec{p}^T \cdot \vec{p}^e_{rel} = \begin{bmatrix} 200 \\ 150 \\ 250 \\ 100 \end{bmatrix}^T \cdot \begin{bmatrix} 0.1 \\ 1.0 \\ 0.2 \\ 1.0 \end{bmatrix} = 320 \text{ kg}$$

As in Chapter 4.4.1, Region C is committed to deliver 50 kWh to Region D using the electricity grid of Region A and Region B. This time, however, the electricity trade is attributed with CO_2 emissions of 0.007 kg CO_2/kWh. In order to correct the system from transit flows, these must be subtracted from the physical electricity flows. Figure 4-13 depicts the correction flows:

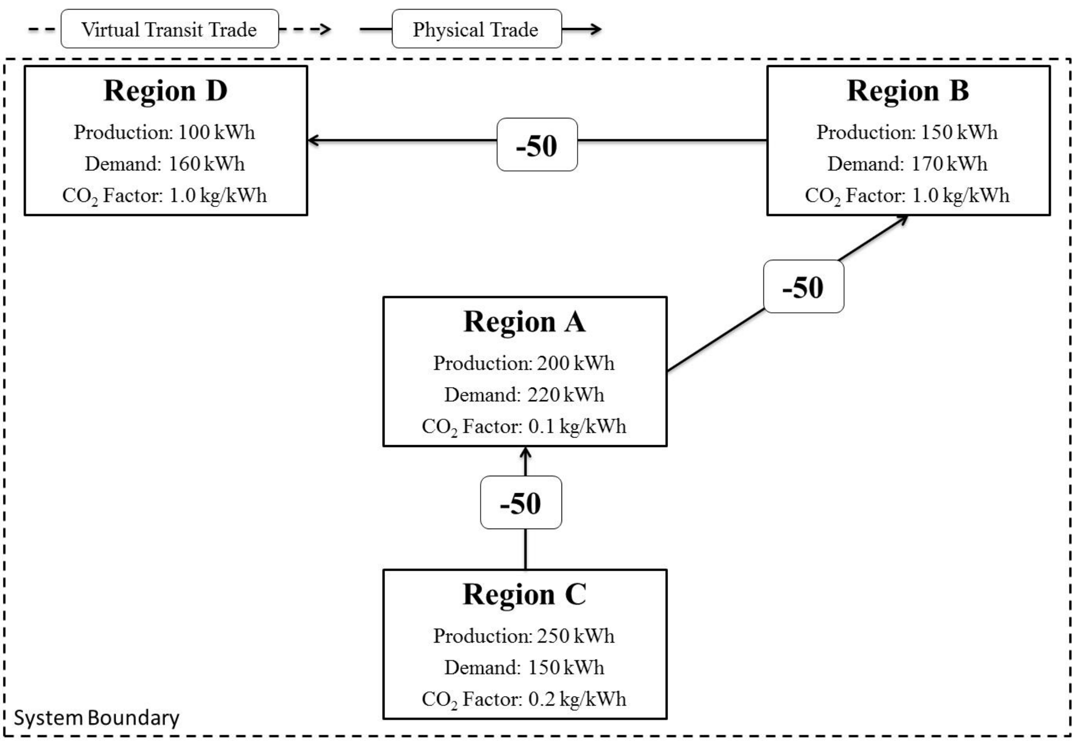

Figure 4-13: Transit-Correction

As a result, the following "Transit-Correction Matrix" $^T_C\boldsymbol{T}$ can be created:

$$^T_CT = \begin{bmatrix} 50 & 0 & -50 & 0 \\ -50 & 50 & 0 & 0 \\ 0 & 0 & 50 & 0 \\ 0 & -50 & 0 & 0 \end{bmatrix}$$

Adding the “Trade-Matrix” **T** and the “Transit-Correction-Matrix $\boldsymbol{{}_{C}^{T}T}$ delivers the “Final Trade Matrix” $\boldsymbol{\breve{T}}$:

$$\breve{T} = T + {}_{C}^{T}T = \begin{bmatrix} 120 & 0 & 100 & 0 \\ 80 & 90 & 0 & 0 \\ 0 & 0 & 150 & 0 \\ 0 & 60 & 0 & 100 \end{bmatrix} + \begin{bmatrix} 50 & 0 & -50 & 0 \\ -50 & 50 & 0 & 0 \\ 0 & 0 & 50 & 0 \\ 0 & -50 & 0 & 0 \end{bmatrix}$$
$$= \begin{bmatrix} 170 & 0 & 50 & 0 \\ 30 & 140 & 0 & 0 \\ 0 & 0 & 200 & 0 \\ 0 & 10 & 0 & 100 \end{bmatrix}$$

Using the Final Trade Matrix $\boldsymbol{\breve{T}}$ and “Relative Production-Emission-Vector” $\boldsymbol{\vec{p}_{rel}^{e}}$ the “Consumption-Emission-Vector” $\boldsymbol{\vec{c}^{e}}$ can be created:

$$\vec{c}^{e} = \breve{T} \cdot \vec{p}_{rel}^{e} = \begin{bmatrix} 170 & 0 & 50 & 0 \\ 30 & 140 & 0 & 0 \\ 0 & 0 & 200 & 0 \\ 0 & 10 & 0 & 100 \end{bmatrix} \cdot \begin{bmatrix} 0.1 \\ 1.0 \\ 0.2 \\ 1.0 \end{bmatrix} = \begin{bmatrix} 27 \\ 143 \\ 40 \\ 110 \end{bmatrix}$$

Now the “Consumption-Emission-Vector” $\vec{c}^e$ is to be corrected by the trade between Region C and Region D. This virtual trade is depicted in Figure 4-14.

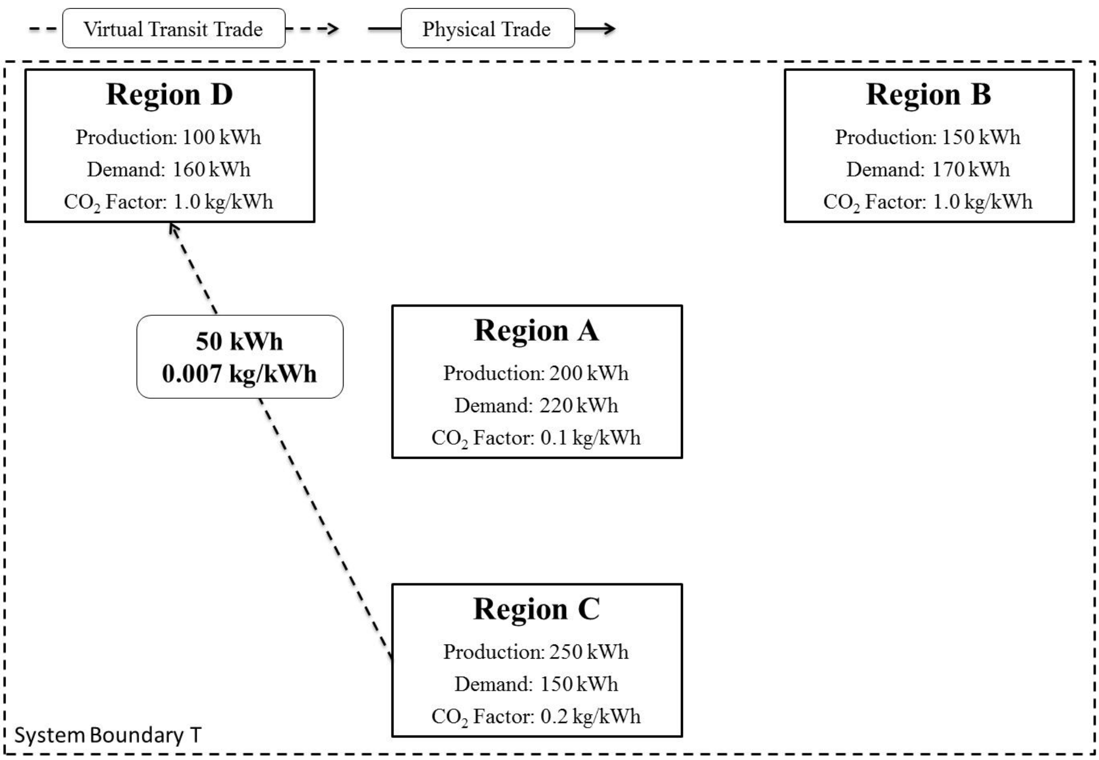

Figure 4-14: Virtual Trade of Electricity

The exported electricity is “green” and therefore attributed with 0.007 kg CO2/ kWh. Region C keeps 50 kWh less of this “green” electricity for its own consumption. The “Virtual Trade-Matrix” ${}^{v}\mathbf{T}$ and the “Virtual Relative Trade-Emission-Vector” ${}^{v}\vec{t}^{e}_{rel}$account for that.

$$^{v}T = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & -50 & 0 \\ 0 & 0 & 50 & 0 \end{bmatrix}$$ **Virtual Trade-Matrix**

$$^{v}\vec{t}^{e}_{rel} = \begin{bmatrix} 0 \\ 0 \\ 0.007 \\ 0 \end{bmatrix}$$ **Virtual Relative Trade-Emission-Vector**

By multiplying the “Virtual Trade-Matrix” $^{v}\mathbf{T}$ and the “Virtual Relative Trade-Emission-Vector”, $^{v}\vec{\boldsymbol{t}}^{\boldsymbol{e}}_{\boldsymbol{rel}}$ the “Virtual Emission-Trade-Vector” $^{v}\vec{\boldsymbol{t}}^{\boldsymbol{e}}$ can be created:

$$^{v}\vec{t}^{e} = {}^{v}T \cdot {}^{v}\vec{t}^{e}_{rel} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & -50 & 0 \\ 0 & 0 & 50 & 0 \end{bmatrix} \cdot \begin{bmatrix} 0 \\ 0 \\ 0.007 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ -0.35 \\ 0.35 \end{bmatrix}$$

Virtual Emission-Trade-Vector

This “Virtual Emission-Trade-Vector” $^{v}\vec{\boldsymbol{t}}^{\boldsymbol{e}}$ is to be added to the “Consumption-Emission-Vector” $\vec{\boldsymbol{c}}^{\boldsymbol{e}}$ in order to compute the “Corrected Consumption-Emission-Vector” $\vec{\boldsymbol{c}}^{\boldsymbol{e}}$.

$$\vec{c}^{e} = \vec{c}^{e} + {}^{v}\vec{t}^{e} = \begin{bmatrix} 27 \\ 143 \\ 40 \\ 110 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ -0.35 \\ 0.35 \end{bmatrix} = \begin{bmatrix} 27 \\ 143 \\ 39.65 \\ 110.35 \end{bmatrix}$$

Now the “Relative Consumption-Emission-Vector” $\vec{\boldsymbol{c}}^{\boldsymbol{e}}_{\boldsymbol{rel}}$ can be computed as follows:

$$\vec{c}^{e}_{rel} = Diag(\vec{c})^{-1} \cdot \vec{c}^{e} = \begin{bmatrix} 220 & 0 & 0 & 0 \\ 0 & 170 & 0 & 0 \\ 0 & 0 & 150 & 0 \\ 0 & 0 & 0 & 160 \end{bmatrix}^{-1} \cdot \begin{bmatrix} 27 \\ 143 \\ 39.65 \\ 110.35 \end{bmatrix} = \begin{bmatrix} 0123 \\ 0.841 \\ 0.264 \\ 0.690 \end{bmatrix}$$

Figure 4-11 visualises the differences between the emissions of the production mix and the emissions of the consumption mix with and without the consideration of the transit of attributed electricity.

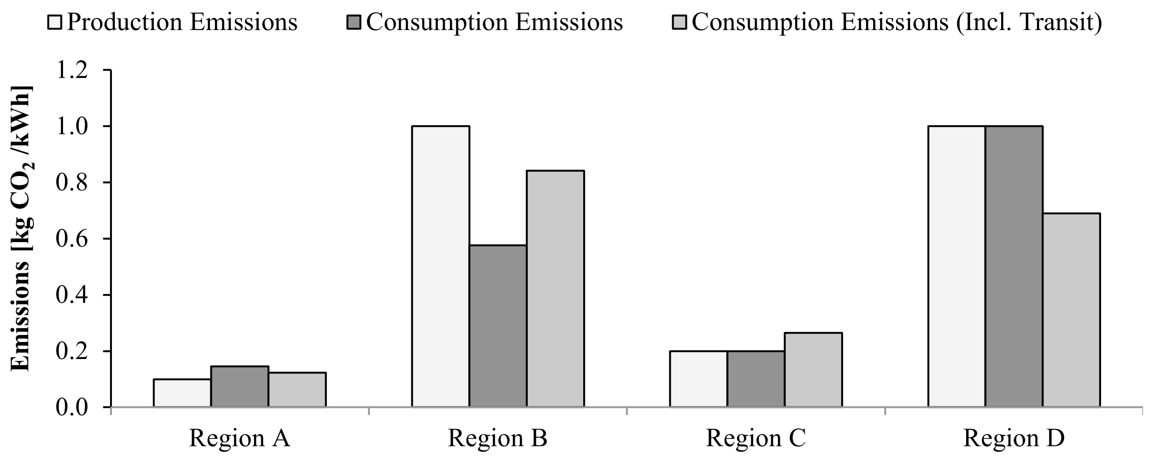

Figure 4-15: Production Emissions vs. Consumption Emissions with and without Transit of Attributed Electricity

Region D can reduce the emissions of the electricity consumption mix significantly by importing "green" electricity from Region C. Region C, however, increases the emissions of the consumption significantly as its low emission electricity is sold to Region D.

4.4.2.2 Contracted Attributed Transit Flows

The example above assumes that the attributed electricity bought into Region D is fed into the overall grid. If the attributed electricity is owned by the final customer, it is not available to the public market. Hence, the consumption emissions have to be corrected. The "Consumption-Vector" $\vec{\boldsymbol{c}}$ is corrected by the amount of electricity already sold to a specific customer using the "Contract-Trade-Vector" ${}^{c}\vec{\boldsymbol{t}}$.

$$\vec{\dot{c}} = \vec{c} - {}^{c}\vec{t} = \begin{bmatrix} 220 \\ 170 \\ 150 \\ 160 \end{bmatrix} - \begin{bmatrix} 0 \\ 0 \\ 0 \\ 50 \end{bmatrix} = \begin{bmatrix} 220 \\ 170 \\ 150 \\ 110 \end{bmatrix}$$

The "Consumption-Emission-Vector" $\vec{c}^e$ is to be corrected by the amount of emissions released by the production of green electricity.

$$\vec{c}^e = \vec{c}^e - Diag({}^{c}\vec{t}) \cdot {}^{c}\vec{t}_{rel} \begin{bmatrix} 27 \\ 143 \\ 39.65 \\ 110.35 \end{bmatrix} - \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 50 \end{bmatrix} \cdot \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0.007 \end{bmatrix} = \begin{bmatrix} 27 \\ 143 \\ 39.65 \\ 110 \end{bmatrix}$$

Now the "Corrected Relative Consumption-Emission-Vector" $\vec{c}^e_{rel}$ can be computed:

$$\vec{c}^e_{rel} = Diag\left(\vec{c}\right)^{-1} \cdot \vec{c}^e = \begin{bmatrix} 220 & 0 & 0 & 0 \\ 0 & 170 & 0 & 0 \\ 0 & 0 & 150 & 0 \\ 0 & 0 & 0 & 110 \end{bmatrix}^{-1} \cdot \begin{bmatrix} 27 \\ 143 \\ 39.65 \\ 110 \end{bmatrix} = \begin{bmatrix} 0123 \\ 0.841 \\ 0.264 \\ 1.000 \end{bmatrix}$$

None of the green electricity Region D purchased from Region C is available to the public market as it is contracted for a specific consumer. As a result, the public market does not profit and the emissions of the consumption mix for Region D remain at 1.0 kg/ kWh.

The procedure described in Chapter 4.4.2 can be summarised using the following equation:

$$\vec{c}^e_{rel} = Diag\left(\vec{c} - {}^{c}\vec{t}\right)^{-1} \cdot \left[\left((T + {}^{T}_{C}T) \cdot \vec{p}^e_{rel}\right) - \left(Diag\left({}^{c}\vec{t}\right) \cdot {}^{c}\vec{t}_{rel}\right) - \left({}^{v}T \cdot {}^{v}\vec{t}^e_{rel}\right)\right]$$

Where the term:

$\boldsymbol{Diag\left(\vec{c} - {}^{c}\vec{t}\right)^{-1}}$	represents the consumption term corrected by contracted electricity
$\boldsymbol{(T + {}^{T}_{C}T)}$	represents the trade relations corrected by transit flows
$\boldsymbol{\vec{p}^e_{rel}}$	represents the production properties

$\boldsymbol{Diag(\,{}^{c}\vec{t})\cdot\ {}^{c}\vec{t}_{rel}}$ represents the directly contracted consumption emissions (which are to be removed from the public market)

$\boldsymbol{{}^{v}T\cdot\ {}^{v}\vec{t}^{e}_{rel}}$ represents the emissions shift through the virtual trade

4.4.3 Summary Module II – Transit Flows

The equations evaluated in Chapter 4.4 can be summarised within the following equation for Module II:

$$\vec{c}^{e}_{rel} = Diag\left(\vec{c} - {}^{c}_{g}\vec{t} - {}^{c}_{a}\vec{t}\right)^{-1} \cdot \left[\left(\left(T + {}^{g}_{C}T + {}^{a}_{C}T\right)\cdot \vec{p}^{e}_{rel}\right) - \left(Diag\left({}^{c}_{a}\vec{t}\right)\cdot {}^{c}_{a}\vec{t}_{rel}\right) - \left({}^{v}_{a}T\cdot\ {}^{v}_{a}\vec{t}^{e}_{rel}\right) - \left(Diag\left({}^{c}_{g}\vec{t}\right) \cdot \left(Diag(\vec{c})^{-1}\, x\, \left(T + {}^{T}_{C}T\right)\right)\cdot \vec{p}^{e}_{rel}\right]$$

Where the term:

$\boldsymbol{Diag\left(\vec{c} - {}^{c}_{g}\vec{t} - {}^{c}_{a}\vec{t}\right)^{-1}}$ represents the consumption term corrected by contracted electricity (grey and attributed)

$\boldsymbol{(T + {}^{g}_{C}T + {}^{a}_{C}T)}$ represents the trade relations corrected by transit flows (grey and attributed)

$\boldsymbol{\vec{p}^{e}_{rel}}$ represents the production properties

$\boldsymbol{Diag({}^{c}_{a}\vec{t})\cdot\ {}^{c}_{a}\vec{t}_{rel}}$ represents the directly contracted attributed consumption emissions (which are therefore to be removed from the public market)

$\boldsymbol{{}^{v}_{a}T\cdot\ {}^{v}_{a}\vec{t}^{e}_{rel}}$ represents the emissions shift through the virtual trade of attributed electricity

$\boldsymbol{Diag}(\,^{c}\vec{t}) \cdot \left(\boldsymbol{Diag}(\vec{\boldsymbol{c}})^{-1} \cdot \left(\boldsymbol{T} + {}_{C}^{T}\boldsymbol{T}\right)\right) \cdot \vec{\boldsymbol{p}}_{\boldsymbol{rel}}^{\boldsymbol{e}}$

represents the directly contracted consumption emissions of grey electricity (which are to be removed from the public market)

In short, it can be written as the following equation:

$$\vec{c}_{rel}^{e} = Diag\left(\vec{c}\right)^{-1} \cdot \left[\left(\breve{T}\; x\; ^{c}\vec{t}\right) - \sum {}^{a}c^{e} - \sum {}^{a}t^{e} - \sum {}^{g}c^{e}\right]$$

Where the term:

$\boldsymbol{Diag}\left(\vec{\boldsymbol{c}}\right)^{-\boldsymbol{1}}$	represents the consumption term corrected by contracted electricity (grey and attributed)
$\breve{\boldsymbol{T}}$	represents the trade relations corrected by transit flows (grey and attributed)
$\vec{\boldsymbol{p}}_{\boldsymbol{rel}}^{\boldsymbol{e}}$	represents the production properties
$\sum {}^{a}c^{e}$	represents the directly contracted attributed consumption emissions (which are therefore to be removed from the public market)
$\sum {}^{a}t^{e}$	represents the emissions shift through the virtual trade of attributed electricity
$\sum {}^{g}c^{e}$	represents the directly contracted consumption emissions of grey electricity (which are therefore to be removed from the public market)

4.5 Module III – Virtual Trade

With certificate trade, it is possible to exchange electricity virtually even if no cable connects the trade partners and no physical delivery of electricity is agreed on.

As for the transition flows grey and attributed electricity certificates can be traded. The implementation procedure into the EMM is described within the following chapters.

4.5.1 Grey Virtual Trade

4.5.1.1 Publicly Available Grey Virtual Trade

When buying grey electricity at the stock exchange, the electricity is automatically attributed with the production mix of the origin country. Figure 4-16 shows the example known from Chapter 4.4.1.

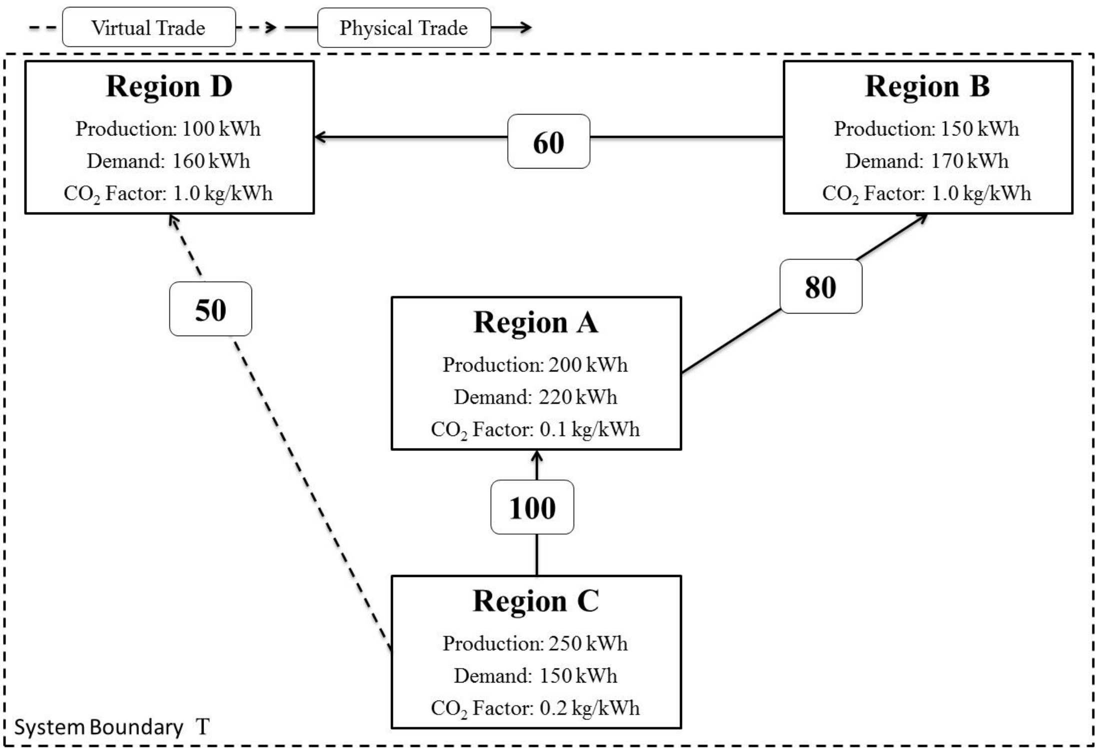

Figure 4-16: Electricity Market System with Grey Virtual Electricity Trade (Example 4)

This time Region D does not receive a physical delivery. Region D merely purchases certificates sold by Region C. Therefore, the approach to account for virtual trade is different from the accounting for transit flows.

In order to analyse this example it is useful to split the virtual trade and the physical trade and evaluate the matrices separately. Figure 4-17 depicts the sole physical trade for the example.

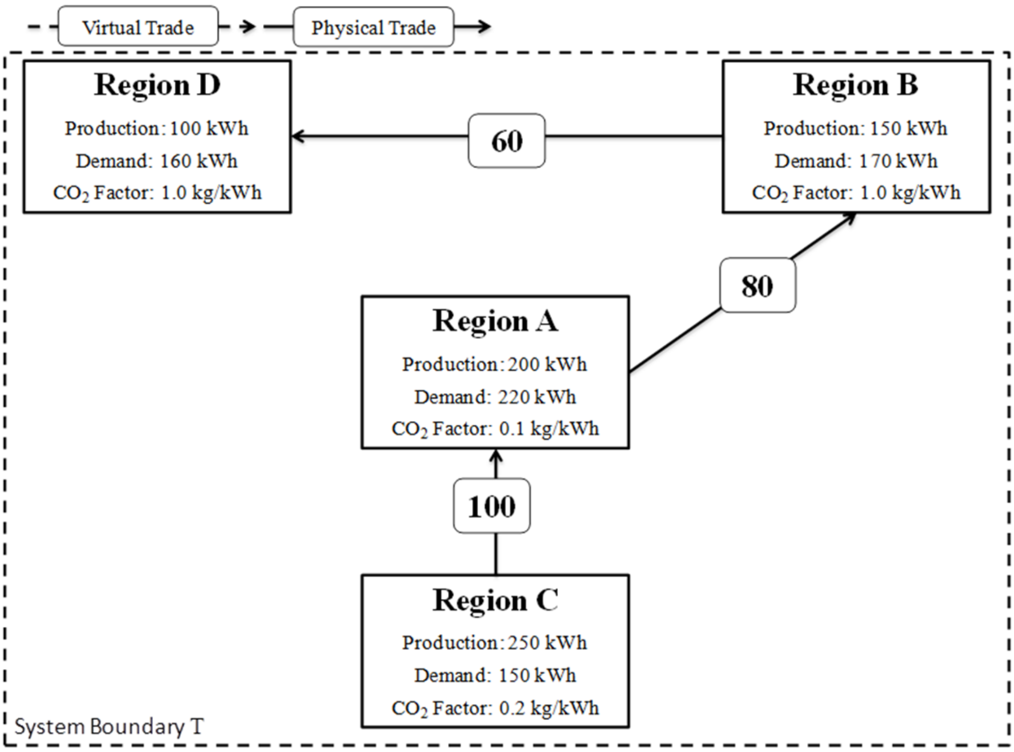

Figure 4-17: Physical Trade of Electricity

A "Trade-Matrix" **T** (only considering physical electricity flows), the "Production-Vector" $\vec{\boldsymbol{p}}$, the "Relative Production-Vector" $\vec{\boldsymbol{p}}^{\boldsymbol{e}}_{\boldsymbol{rel}}$ and the "Consumption-Vector" $\vec{\boldsymbol{c}}$ are defined as follows:

$$T = \begin{bmatrix} 120 & 0 & 100 & 0 \\ 80 & 90 & 0 & 0 \\ 0 & 0 & 150 & 0 \\ 0 & 60 & 0 & 100 \end{bmatrix} \qquad \vec{p} = \begin{bmatrix} 200 \\ 150 \\ 250 \\ 100 \end{bmatrix}$$

$$\vec{p}^{e}_{rel} = \begin{bmatrix} 0.1 \\ 1.0 \\ 0.2 \\ 1.0 \end{bmatrix} \qquad \vec{c} = \begin{bmatrix} 220 \\ 170 \\ 150 \\ 160 \end{bmatrix}$$

The total carbon balance can be computed using the "Production-Vector" $\vec{\boldsymbol{p}}$ and the "Relative Production-Emission-Vector" $\vec{\boldsymbol{p}}^{\boldsymbol{e}}_{\boldsymbol{rel}}$:

$$\vec{p}^T \cdot \vec{p}^e_{rel} = \begin{bmatrix} 200 \\ 150 \\ 250 \\ 100 \end{bmatrix}^T \cdot \begin{bmatrix} 0.1 \\ 1.0 \\ 0.2 \\ 1.0 \end{bmatrix} = 320 \text{ kg}$$

The total CO_2 emissions of the system amount to 320 kg. As the geographical border represents an enclosed system, no emissions can leave or enter the system. Hence, Region C sells low carbon electricity virtually and receives the attributes of the same amount of electricity produced by Region D. Therefore, the total carbon balance must remain 320 kg. For a better understanding, the sole virtual trade is visualised in Figure 4-18.

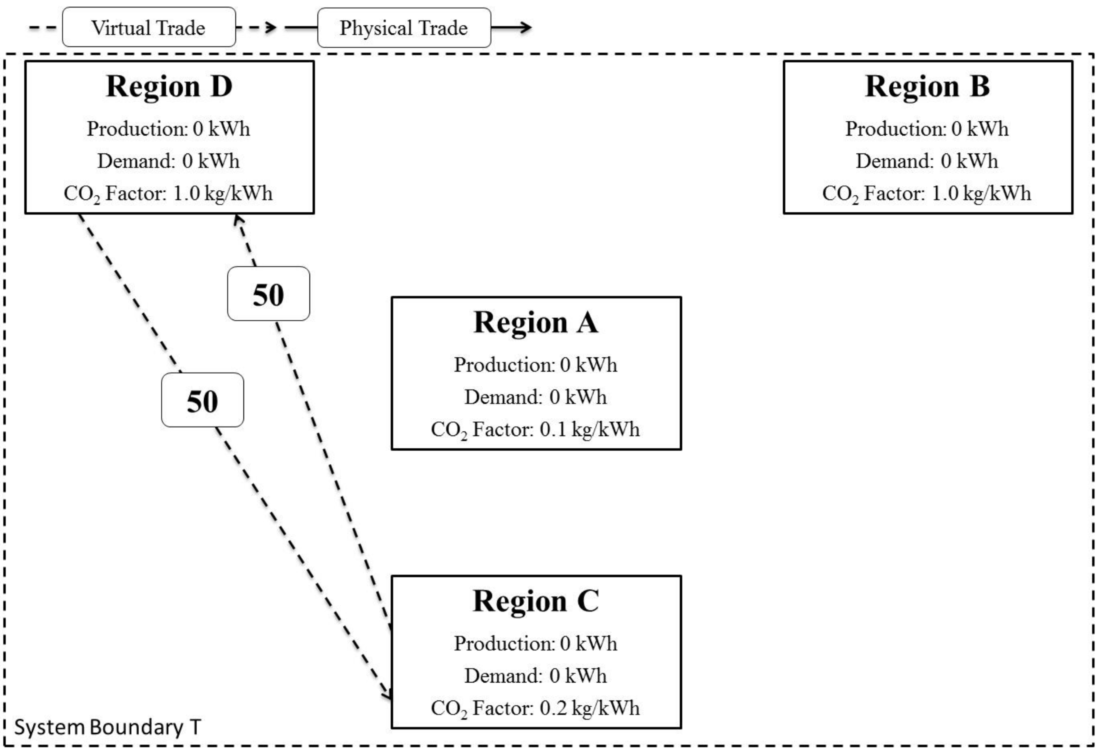

Figure 4-18: Virtual Trade of Electricity

A "Virtual Trade-Matrix" $^{v}\mathbf{T}$ (only considering virtual electricity flows) is defined as follows:

$$^{v}T = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & -50 & 50 \\ 0 & 0 & 50 & -50 \end{bmatrix}$$

The negative values ensue because Region C and Region D each export 50 kWh. Hence, 50 kWh less of electricity are left for each region's own consumption.

The next step is adding the "Virtual Trade Matrix" ${}^{v}\mathbf{T}$ to the "Trade Matrix" **T** in order to receive the "Final-Trade-Matrix" $\check{\mathbf{T}}$**.**

$$\check{T} = T + {}^{v}T = \begin{bmatrix} 120 & 0 & 100 & 0 \\ 80 & 90 & 0 & 0 \\ 0 & 0 & 150 & 0 \\ 0 & 60 & 0 & 100 \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & -50 & 50 \\ 0 & 0 & 50 & -50 \end{bmatrix} = \begin{bmatrix} 120 & 0 & 100 & 0 \\ 80 & 90 & 0 & 0 \\ 0 & 0 & 100 & 50 \\ 0 & 60 & 50 & 50 \end{bmatrix}$$

With the "Final-Trade-Matrix" $\check{\mathbf{T}}$ and the "Relative Production-Vector" $\vec{\boldsymbol{p}}^{\boldsymbol{e}}_{\boldsymbol{rel}}$ the "Corrected Consumption-Emission-Vector" $\vec{\boldsymbol{c}}^{\boldsymbol{e}}$ can be computed:

$$\vec{c}^{e} = \check{T} \cdot \vec{p}^{e}_{rel} = \begin{bmatrix} 120 & 0 & 100 & 0 \\ 80 & 90 & 0 & 0 \\ 0 & 0 & 100 & 50 \\ 0 & 60 & 50 & 50 \end{bmatrix} \cdot \begin{bmatrix} 0.1 \\ 1.0 \\ 0.2 \\ 1.0 \end{bmatrix} = \begin{bmatrix} 32 \\ 98 \\ 70 \\ 120 \end{bmatrix}$$

The "Corrected Relative Consumption-Emission-Vector" $\vec{\boldsymbol{c}}^{\boldsymbol{e}}_{\boldsymbol{rel}}$ amounts to:

$$\vec{c}^{e}_{rel} = Diag(\vec{c})^{-1} \cdot \vec{c}^{e} = \begin{bmatrix} 220 & 0 & 0 & 0 \\ 0 & 170 & 0 & 0 \\ 0 & 0 & 150 & 0 \\ 0 & 0 & 0 & 160 \end{bmatrix}^{-1} \cdot \begin{bmatrix} 32 \\ 98 \\ 70 \\ 120 \end{bmatrix} = \begin{bmatrix} 0.145 \\ 0.576 \\ 0.467 \\ 0.750 \end{bmatrix}$$

Figure 4-19 shows the differences between the production emissions and the consumption emissions with and without certificates, respectively.

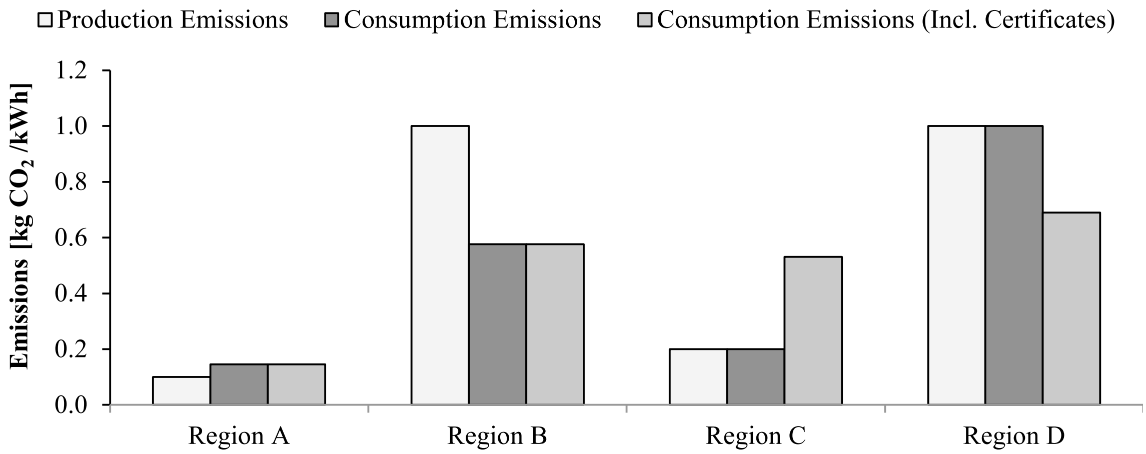

Figure 4-19: Production Emissions vs. Consumption Emissions with and without Grey Virtual Electricity Trade

As a result, Region D can reduce the emissions of the electricity consumption mix significantly by importing "green" certificates from Region C. Region C, however, increases the emissions of the consumption significantly as attributes of low emission electricity are sold to Region D.

4.5.1.2 Contracted Grey Virtual Trade

The example above assumes that the certificates for grey electricity bought into Region D are fed into the overall grid. Again, grey electricity can be owned by a final customer and is therefore not available for the public market. Therefore, these certificates have to be corrected and removed from the market. This can be achieved by correcting the "Consumption-Vector" $\vec{\boldsymbol{c}}$ by the amount of electricity already sold to a specific customer, resulting in the "Contract-Trade-Vector" ${}^{c}\vec{\boldsymbol{t}}$. The following example assumes that the emissions Region C receives from Region D are not brought into the market of Region C.

$$\vec{\tilde{c}} = \vec{c} - {}^{c}\vec{t} = \begin{bmatrix} 220 \\ 170 \\ 150 \\ 160 \end{bmatrix} - \begin{bmatrix} 0 \\ 0 \\ 0 \\ 50 \end{bmatrix} = \begin{bmatrix} 220 \\ 170 \\ 150 \\ 110 \end{bmatrix}$$

The "Consumption-Emission-Vector" $\vec{\boldsymbol{c}}^{\boldsymbol{e}}$ is to be corrected by the amount of emissions the sold grey electricity is responsible for.

$$\vec{c}^{e} = \vec{c}^{e} - Diag\left(\overrightarrow{{}^{c}t}\right) \cdot {}^{c}\vec{\mathrm{t}}_{rel} = \begin{bmatrix} 32 \\ 98 \\ 70 \\ 120 \end{bmatrix} - \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 50 \end{bmatrix} \cdot \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0.2 \end{bmatrix} = \begin{bmatrix} 32 \\ 98 \\ 70 \\ 110 \end{bmatrix}$$

Now the "Relative Consumption-Emission-Vector" $\vec{\boldsymbol{c}}^{\boldsymbol{e}}_{\boldsymbol{rel}}$ can be computed.

$$\vec{c}^{e}_{rel} = Diag\left(\vec{c}\right)^{-1} \cdot \vec{c}^{e} = \begin{bmatrix} 220 & 0 & 0 & 0 \\ 0 & 170 & 0 & 0 \\ 0 & 0 & 150 & 0 \\ 0 & 0 & 0 & 110 \end{bmatrix}^{-1} \cdot \begin{bmatrix} 32 \\ 98 \\ 70 \\ 110 \end{bmatrix} = \begin{bmatrix} 0.145 \\ 0.576 \\ 0.467 \\ 1.000 \end{bmatrix}$$

None of the grey electricity Region D purchased from Region C is available for the public market as a specific consumer contracts it. As a result, the public market does not profit and the emissions of the consumption mix for Region D remain at 1.0 kg/kWh. The following equation summarises the procedure evaluated above:

$$\vec{c}^{e}_{rel} = Diag\left(\vec{\boldsymbol{c}} - {}^{\boldsymbol{c}}\vec{\boldsymbol{t}}\right)^{-1} \cdot \left[\left((T \cdot \vec{p}^{e}_{rel}) - \left(Diag\left({}^{c}\vec{t}\right) \cdot {}^{c}\vec{\mathrm{t}}_{rel}\right) - \left({}^{v}T \cdot {}^{v}\vec{t}^{e}_{rel}\right)\right)\right]$$

Where the term:

$\boldsymbol{Diag}\left(\vec{\boldsymbol{c}} - {}^{\boldsymbol{c}}\vec{\boldsymbol{t}}\right)^{-\mathbf{1}}$	represents the consumption term corrected by contracted electricity
$\boldsymbol{T}$	represents the trade relations

$\vec{\boldsymbol{p}}^{\boldsymbol{e}}_{\boldsymbol{rel}}$	represents the production properties
$\boldsymbol{Diag}({}^{c}\vec{\boldsymbol{t}}) \cdot {}^{c}\vec{\mathbf{t}}_{\boldsymbol{rel}}$	represents the directly contracted consumption emissions (which are therefore to removed from the public market)
${}^{v}\boldsymbol{T} \cdot {}^{v}\vec{\boldsymbol{t}}^{\boldsymbol{e}}_{\boldsymbol{rel}}$	represents the emissions shift through the virtual trade

4.5.2 Attributed Virtual Trade

4.5.2.1 Public Attributed Virtual Trade

In Chapter 4.5.1 only grey electricity is analysed. In most cases, however, electricity is traded with a certain attribute. This attribute can be generally "green" electricity or can refer to a certain technology e.g. water, or wind power. In Germany in 2012 an estimate of 21 TWh (ca. 4% of the total electricity consumption) (Energie und Management) green electricity was sold with a strong upward tendency. Therefore, an incorporation of attributed electricity into the model is necessary. The following chapters introduce the consideration into the model using a simple example. Figure 4-20 visualises the trade mechanism.

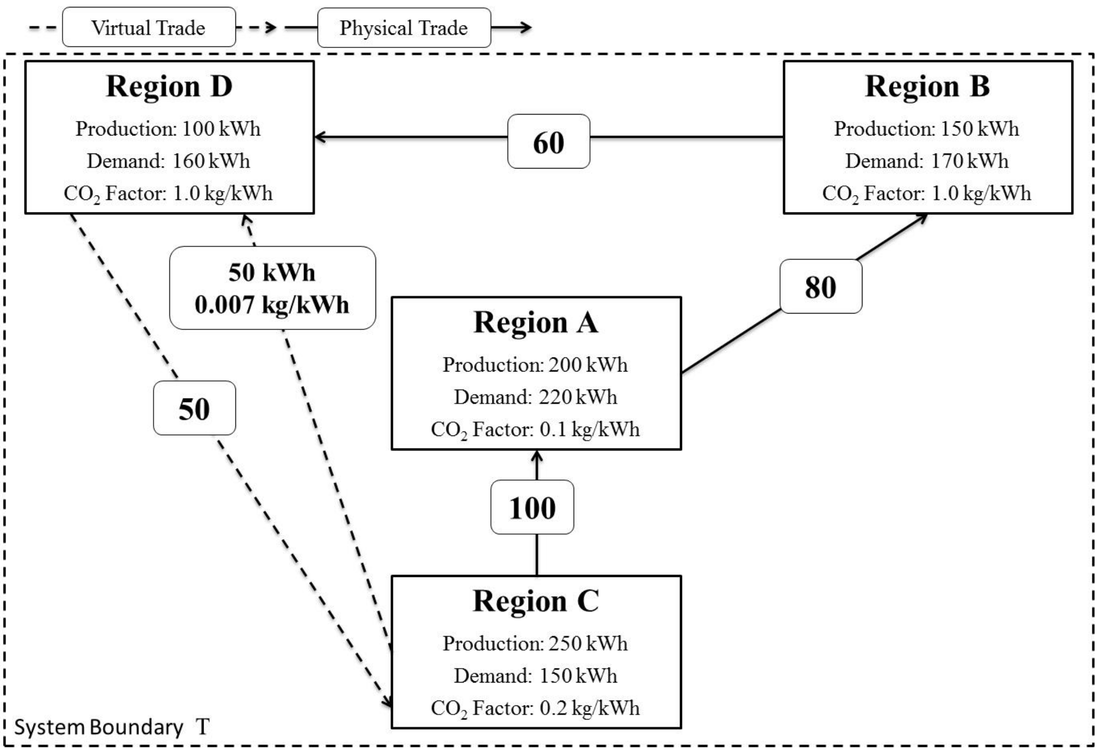

Figure 4-20: Virtual Trade of Attributed Electricity (Example 5)

The situation is similar to that in Chapter 4.4.2. Region C, however, does now sell electricity produced by a specific technology (e.g. wind power) which is attributed with 0.007 kg/kWh. Again, physical and virtual flows are examined separately. Figure 4-17 depicts the sole physical trade for this example.

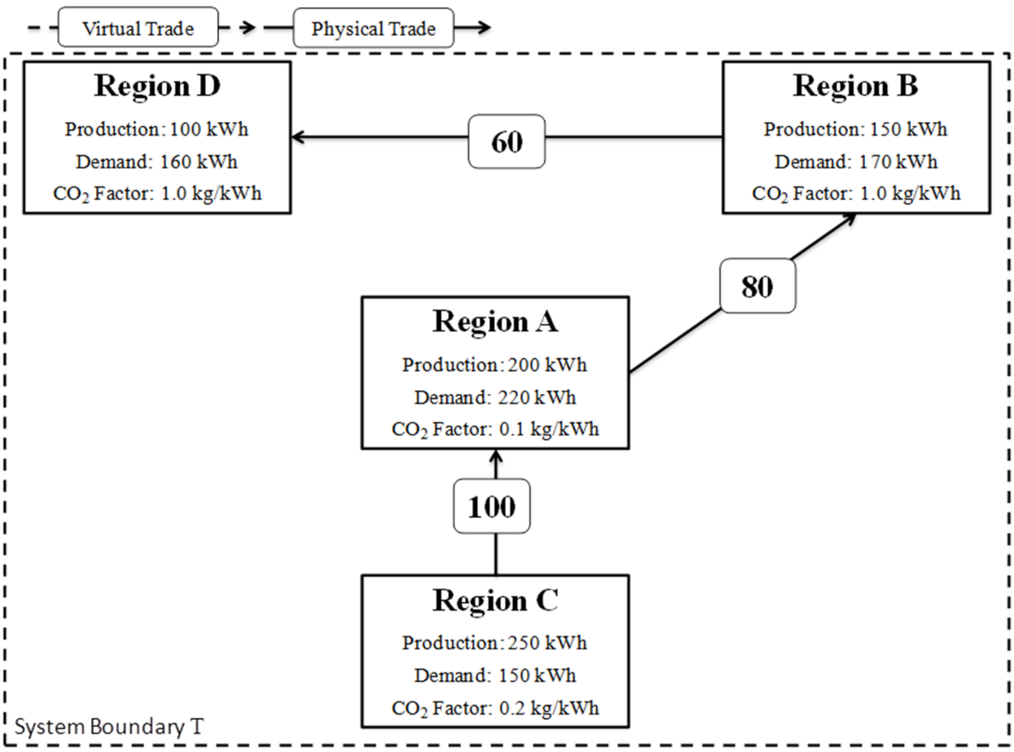

Figure 4-21: Physical Trade

A "Trade-Matrix" **T** (only considering physical electricity flows), the "Production-Vector" $\vec{\boldsymbol{p}}$, the "Relative Production-Vector" $\vec{\boldsymbol{p}}^{\boldsymbol{e}}_{\boldsymbol{rel}}$ and the "Consumption-Vector" $\vec{\boldsymbol{c}}$ are defined as follows:

$$T = \begin{bmatrix} 120 & 0 & 100 & 0 \\ 80 & 90 & 0 & 0 \\ 0 & 0 & 150 & 0 \\ 0 & 60 & 0 & 100 \end{bmatrix} \qquad \vec{p} = \begin{bmatrix} 200 \\ 150 \\ 250 \\ 100 \end{bmatrix}$$

$$\vec{p}^{e}_{rel} = \begin{bmatrix} 0.1 \\ 1.0 \\ 0.2 \\ 1.0 \end{bmatrix} \qquad \vec{c} = \begin{bmatrix} 220 \\ 170 \\ 150 \\ 160 \end{bmatrix}$$

The total carbon balance can be computed using the Production-Vector" $\vec{\boldsymbol{p}}$ and the "Relative Production-Emission-Vector" $\vec{\boldsymbol{p}}^{\boldsymbol{e}}_{\boldsymbol{rel}}$:

$$\vec{p}^{T} \cdot \vec{p}^{e}_{rel} = \begin{bmatrix} 0.1 \\ 1.0 \\ 0.2 \\ 1.0 \end{bmatrix}^{T} \cdot \begin{bmatrix} 200 \\ 150 \\ 250 \\ 100 \end{bmatrix} = 320 \text{ kg}$$

The total CO_2 emissions of the system amount to 320 kg.

The "Trade-Matrix" **T** multiplied with the "Relative Production-Emission-Vector" $\vec{\boldsymbol{p}}^{\boldsymbol{e}}_{\boldsymbol{rel}}$ is the following:

$$\vec{c}^{e} = T \cdot \vec{p}^{e}_{rel} = \begin{bmatrix} 120 & 0 & 100 & 0 \\ 80 & 90 & 0 & 0 \\ 0 & 0 & 150 & 0 \\ 0 & 60 & 0 & 100 \end{bmatrix} \cdot \begin{bmatrix} 0.1 \\ 1.0 \\ 0.2 \\ 1.0 \end{bmatrix} = \begin{bmatrix} 32 \\ 98 \\ 30 \\ 160 \end{bmatrix}$$

The relative consumption emissions without consideration of certificate trade are:

$$\vec{c}^{e}_{rel} = Diag(\vec{c})^{-1} \cdot \vec{c}^{e} = \begin{bmatrix} 220 & 0 & 0 & 0 \\ 0 & 170 & 0 & 0 \\ 0 & 0 & 150 & 0 \\ 0 & 0 & 0 & 160 \end{bmatrix}^{-1} \cdot \begin{bmatrix} 32 \\ 98 \\ 30 \\ 160 \end{bmatrix} = \begin{bmatrix} 0.145 \\ 0.576 \\ 0.200 \\ 1.000 \end{bmatrix}$$

Now the consumption emissions are to be corrected by the virtual trade as visualised in Figure 4-22.

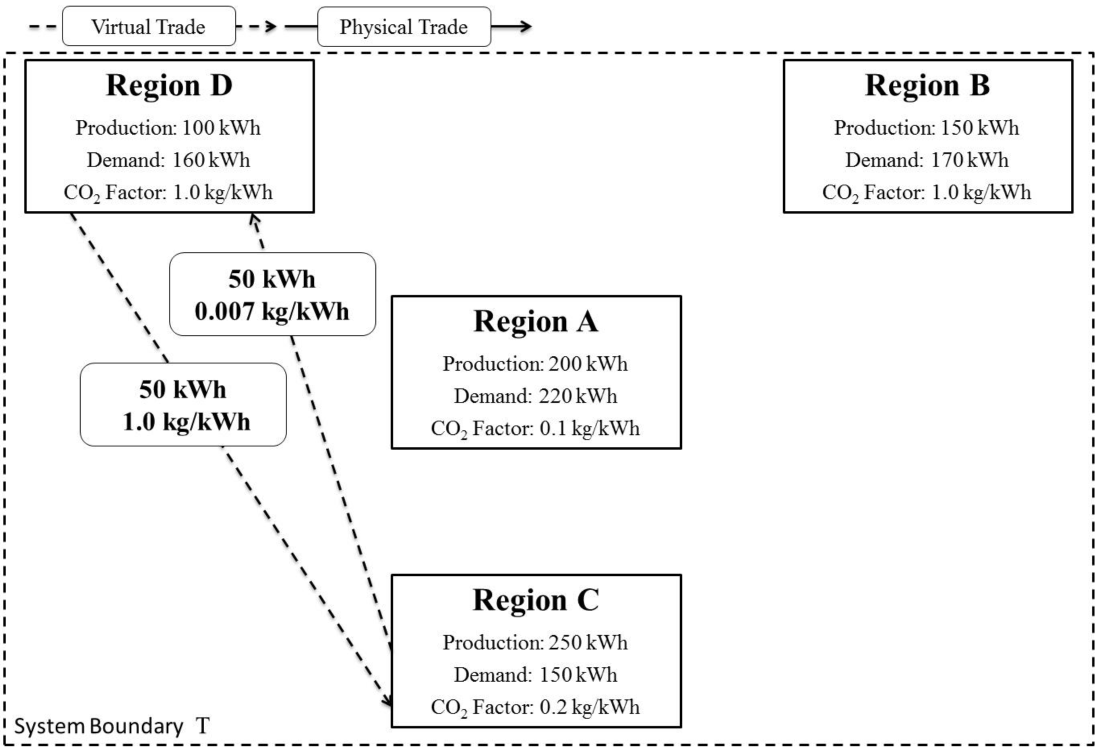

Figure 4-22: Virtual Trade of Attributed Electricity

The virtual electricity Region C exports to Region D is attributed with 0.007 kg CO_2/kWh. The virtual electricity Region D receives back equals the emissions of the consumption mix of Region D. The "Virtual Trade-Matrix" $^{v}\mathbf{T}$ and the "Virtual Relative Trade-Emission-Vector " $^{v}\vec{\boldsymbol{t}}^{\boldsymbol{e}}_{\boldsymbol{rel}}$ account for that.

$$^{v}T = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & -50 & 50 \\ 0 & 0 & 50 & -50 \end{bmatrix} \qquad {}^{v}\vec{t}^{e}_{rel} = \begin{bmatrix} 0 \\ 0 \\ 0.007 \\ 1.000 \end{bmatrix}$$

By multiplying the "Virtual Trade-Matrix" $^{v}\mathbf{T}$ and the "Virtual Relative Trade-Emission-Vector", $^{v}\vec{\boldsymbol{t}}^{\boldsymbol{e}}_{\boldsymbol{rel}}$ the "Virtual Emission-Trade-Vector" $^{v}\vec{\boldsymbol{t}}^{\boldsymbol{e}}$ can be created:

$$
{}^{v}\vec{t}^{\,e} = {}^{v}T \cdot {}^{v}\vec{t}^{\,e}_{rel} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & -50 & 50 \\ 0 & 0 & 50 & -50 \end{bmatrix} \cdot \begin{bmatrix} 0 \\ 0 \\ 0.007 \\ 1.000 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 49.65 \\ -49.65 \end{bmatrix}
$$

This "Virtual Emission-Trade-Vector" ${}^{\boldsymbol{v}}\vec{\boldsymbol{t}}^{\boldsymbol{e}}$ is to be added to the "Consumption-Emission-Vector" $\vec{\boldsymbol{c}}^{\boldsymbol{e}}$ in order to compute the "Corrected Consumption-Emission-Vector" $\vec{\boldsymbol{c}}^{\boldsymbol{e}}$.

$$
\vec{c}^{\,e} = \vec{c}^{\,e} + {}^{v}\vec{t}^{\,e} = \begin{bmatrix} 32 \\ 98 \\ 30 \\ 160 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 49.65 \\ -49.65 \end{bmatrix} = \begin{bmatrix} 32 \\ 98 \\ 79.65 \\ 110.35 \end{bmatrix}
$$

Now the "Corrected Relative Consumption-Emission-Vector" $\vec{\boldsymbol{c}}^{\boldsymbol{e}}_{\boldsymbol{rel}}$ can be computed as follows:

$$
\vec{c}^{\,e}_{rel} = Diag(\vec{c})^{-1} \cdot \vec{c}^{\,e} = \begin{bmatrix} 220 & 0 & 0 & 0 \\ 0 & 170 & 0 & 0 \\ 0 & 0 & 150 & 0 \\ 0 & 0 & 0 & 160 \end{bmatrix}^{-1} \cdot \begin{bmatrix} 32 \\ 98 \\ 79.65 \\ 110.35 \end{bmatrix} = \begin{bmatrix} 0.145 \\ 0.576 \\ 0.531 \\ 0.690 \end{bmatrix}
$$

Figure 4-23 visualises the differences between the emissions of the production mix and the emissions of the consumption mix with and without the consideration of the transiting of attributed electricity.

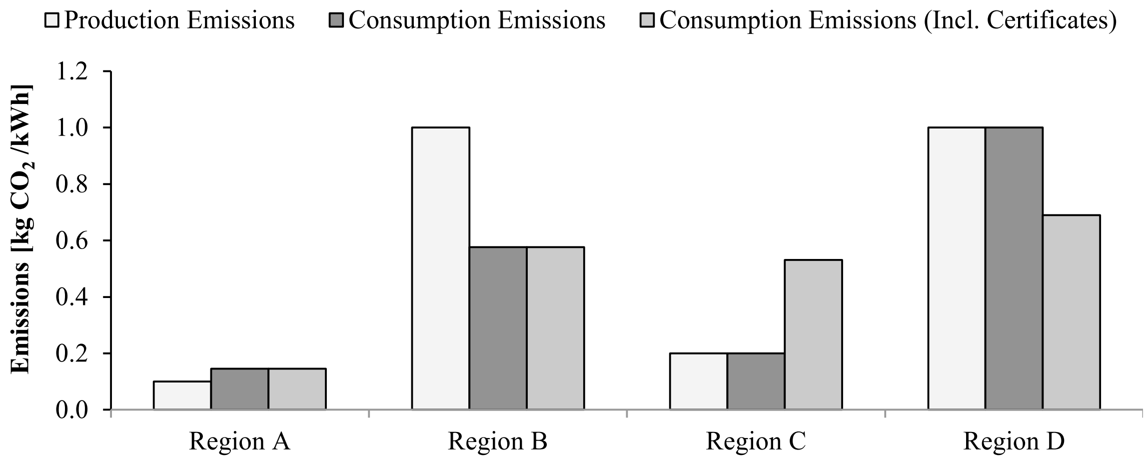

Figure 4-23: Production Emissions vs. Consumption Emissions with and without Attributed Virtual Electricity Trade

Region D can reduce the emissions of the consumption mix significantly by importing green electricity from Region C. Region C, however, increases the emissions of the consumption significantly as the low emission electricity is sold to Region D.

4.5.2.2 Contracted "Attributed" Virtual Trade

The example above assumes that the attributed electricity certificates bought into Region D are fed into the overall grid. If the final customer owns attributed electricity certificates, they have to be removed from the public market. Since the consumption emission calculation of this study aims at assessing the public market and not merely a specific customer, this has to be corrected. The "Consumption-Vector" $\vec{\boldsymbol{c}}$ is corrected by the amount of electricity already sold to a specific customer by the "Contract-Trade-Vector" ${}^{c}\vec{\boldsymbol{t}}$.

$$\vec{\acute{c}} = \vec{c} - {}^{c}\vec{t} = \begin{bmatrix} 220 \\ 170 \\ 150 \\ 160 \end{bmatrix} - \begin{bmatrix} 0 \\ 0 \\ 0 \\ 50 \end{bmatrix} = \begin{bmatrix} 220 \\ 170 \\ 150 \\ 110 \end{bmatrix}$$

The “Consumption-Emission-Vector” $\vec{\boldsymbol{c}}^{\boldsymbol{e}}$ is to be corrected by the amount of emissions the sold green electricity generated.

$$\vec{c}^{e} = \vec{c}^{e} - Diag(\,{}^{c}\vec{t}) \cdot \,{}^{c}\vec{\mathrm{t}}_{rel} \begin{bmatrix} 32 \\ 98 \\ 79.65 \\ 110.35 \end{bmatrix} - \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 50 \end{bmatrix} \cdot \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0.007 \end{bmatrix} = \begin{bmatrix} 32 \\ 98 \\ 79.65 \\ 110 \end{bmatrix}$$

Now the “Relative Consumption-Emission-Vector” $\vec{\boldsymbol{c}}^{\boldsymbol{e}}_{\boldsymbol{rel}}$ can be computed.

$$\vec{c}^{e}_{rel} = Diag\left(\vec{c}\right)^{-1} \cdot \vec{c}^{e} = \begin{bmatrix} 220 & 0 & 0 & 0 \\ 0 & 170 & 0 & 0 \\ 0 & 0 & 150 & 0 \\ 0 & 0 & 0 & 110 \end{bmatrix}^{-1} \cdot \begin{bmatrix} 32 \\ 98 \\ 79.65 \\ 110 \end{bmatrix} = \begin{bmatrix} 0.145 \\ 0.576 \\ 0.531 \\ 1.000 \end{bmatrix}$$

None of the green electricity Region D purchased from Region C is available to the public market as it is contracted for a specific consumer. As a result, the public market does not profit and the emissions of the consumption mix for Region D remain at 1.0 kg/kWh.

4.5.3 Summary Module III – Virtual Trade

The procedure described in Chapter 0 can be summarised with the following equation:

$$\vec{c}^{e}_{rel} = Diag\left(\vec{\boldsymbol{c}} - \,{}^{\boldsymbol{c}}\vec{\boldsymbol{t}}\right)^{-1} \cdot \left[\left(T \cdot \vec{p}^{e}_{rel}\right) - \left(Diag\left(\,{}^{\boldsymbol{c}}\vec{\boldsymbol{t}}\right) \cdot \,{}^{c}\vec{\mathrm{t}}_{rel}\right) - \left(\,{}^{v}T \cdot \,{}^{v}\vec{t}^{e}_{rel}\right)\right]$$

Where the term:

$\boldsymbol{Diag}\left(\vec{\boldsymbol{c}} - \,{}^{\boldsymbol{c}}\vec{\boldsymbol{t}}\right)^{-\boldsymbol{1}}$ represents the consumption term corrected by contracted electricity

$\boldsymbol{T}$	represents the trade relations corrected by transit flows
$\vec{\boldsymbol{p}}^{e}_{\boldsymbol{rel}}$	represents the production properties
$\boldsymbol{Diag}(\,{}^{c}\vec{\boldsymbol{t}}) \cdot \;{}^{c}\vec{\mathbf{t}}_{\boldsymbol{rel}}$	represents the directly contracted consumption emissions (which are consequently to be removed from the public market)
${}^{v}\boldsymbol{T} \cdot \;{}^{v}\vec{\boldsymbol{t}}^{e}_{\boldsymbol{rel}}$	represents the emissions shift through virtual trade

4.6 Aggregation of Modules I - III

The equations evaluated in Chapter 4.5 can be summarised within in the following equation representing Module I - III:

$$\vec{c}^{\,e}_{rel} = Diag\left(\vec{c} - {}^{c}_{g}\vec{t} - {}^{c}_{a}\vec{t}\right)^{-1} \cdot \left[\left(T\,x\,\vec{p}^{\,e}_{rel}\right) - \left(Diag\left({}^{c}_{a}\vec{t}\right) \cdot \;{}^{c}_{a}\vec{t}^{\,e}_{rel}\right) - \left(\,{}^{v}T \cdot \;{}^{v}_{a}\vec{t}^{\,e}_{rel}\right) - \left(Diag\left(\overrightarrow{{}^{c}_{g}t}\right) \cdot \left(Diag(\overrightarrow{c_i})^{-1} \;\cdot\; T\right) \cdot \;\vec{p}^{\,e}_{rel}\,\right]$$

Where the term:

$\boldsymbol{Diag}\left(\vec{\boldsymbol{c}} - {}^{c}_{g}\vec{\boldsymbol{t}} - {}^{c}_{a}\vec{\boldsymbol{t}}\right)^{-\mathbf{1}}$	represents the consumption term corrected by contracted electricity (grey and attributed)
$\boldsymbol{T}$	represents the physical trade relations
$\vec{\boldsymbol{p}}^{e}_{\boldsymbol{rel}}$	represents the production properties
$\boldsymbol{Diag}\left({}^{c}_{a}\vec{\boldsymbol{t}}\right) \cdot \;{}^{c}_{a}\vec{\boldsymbol{t}}^{e}_{\boldsymbol{rel}}$	represents the directly contracted attributed consumption emissions (which are therefore to be removed from the public market)
${}^{v}_{a}\boldsymbol{T} \cdot \;{}^{v}_{a}\vec{\boldsymbol{t}}^{e}_{\boldsymbol{rel}}$	represents the emissions shift through the virtual trade of attributed electricity

$\boldsymbol{Diag}({}^{c}\vec{\boldsymbol{t}}) \cdot (\boldsymbol{Diag}(\vec{\boldsymbol{c}})^{-1} \cdot \boldsymbol{T}) \cdot \vec{\boldsymbol{p}}^{e}_{\boldsymbol{rel}}$

represents the directly contracted consumption emissions of grey electricity (which are therefore to be removed from the public market)

Using a short Equation, it can be written in the following equation:

$$\vec{c}^{e}_{rel} = Diag\left(\vec{\breve{c}}\right)^{-1} \cdot \left[\left(\breve{T} \cdot \vec{p}^{e}_{rel}\right) - \sum {}^{a}c^{e} - \sum {}^{a}t^{e} - \sum {}^{g}c^{e}\right]$$

Where the term:

$\boldsymbol{Diag}\left(\vec{\breve{\boldsymbol{c}}}\right)^{-\boldsymbol{1}}$	represents the consumption term corrected by contracted electricity (grey and attributed)
$\breve{\boldsymbol{T}}$	represents the trade relations corrected by transit flows (grey and attributed)
$\vec{\boldsymbol{p}}^{e}_{\boldsymbol{rel}}$	represents the production properties
$\sum {}^{a}c^{e}$	represents the directly contracted attributed consumption emissions (which are therefore to be removed from the public market)
$\sum {}^{a}t^{e}$	represents the emissions shift through the virtual trade of attributed electricity
$\sum {}^{g}c^{e}$	represents the directly contracted consumption emissions of grey electricity (which are therefore to be removed from the public market)

The mathematical evaluation of the physical and virtual trade is the key to an automated calculation requiring vast amounts of data.

When data on transited flows and virtual trade is available, the precision of a LCA can be increased significantly. For the virtual trade, however, an annual time resolution is reasonable as certificates are usually accounted for over the course of a calendar year (European Commission 2009). For a high time resolution, average values of an annual consumption can be used (annual/8760 h).

The evaluated model is transferred to Microsoft Excel (2010) and a Visual Basic Application (VBA) Macro based tool is programmed to carry out the calculations. This Excel based model represents an interface between high-resolution power plant data and electricity exchange data (in this study the DIMENSION Model (EWI 2011)) and the GaBi LCI data of power plants (PE International 2013) as depicted in Figure 4-24.

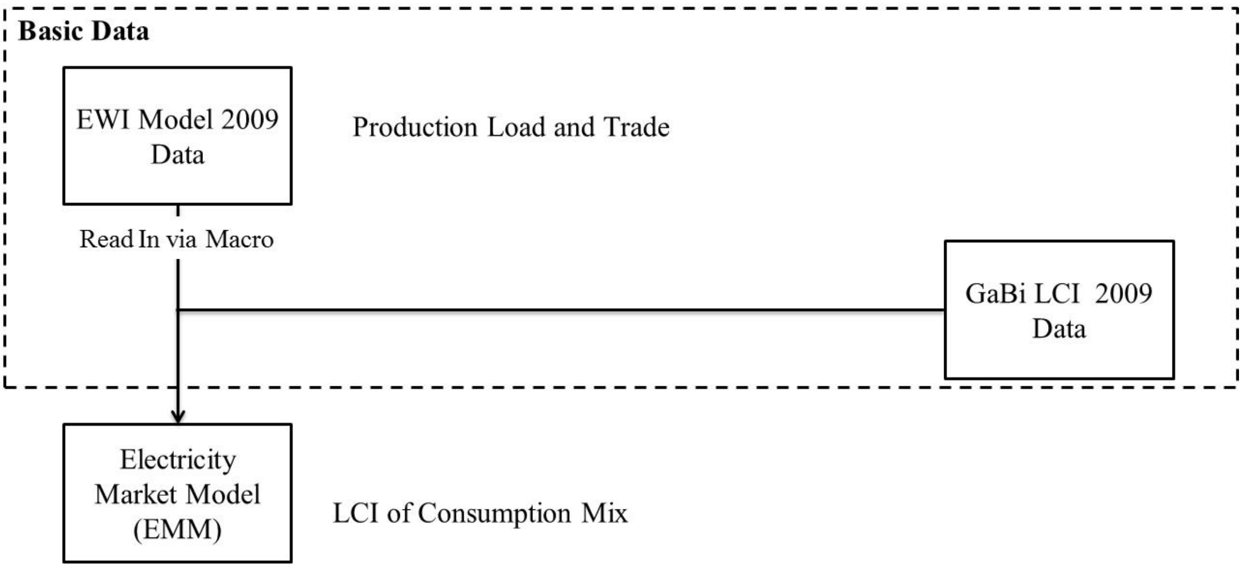

Figure 4-24: Database of the EMM

The following chapter describes the considerations of electricity storage systems in the EMM.

4.7 Consideration of Electricity Storage Systems

Electricity storage applications are crucial to support the balance of supply and demand. A rising share of renewables in an energy system results in stronger variations in the supply. These supply variations are mostly non-proportional to the demand. In times of strong wind and/or high insolation, levels, excess electricity is generated which can be stored by a wide range of technologies on different efficiency levels. The most reliable and affordable electricity storage option in Europe is pump storage with a total installed capacity of 39 GW in 2009

(PAPAGEORGI, A. 2009). An increase of capacities is somewhat limited in the modelled European countries due to a lack of suitable locations (LACAL-ARÁNTEGUI, R. et al. 2012). It can be assumed that other electricity storage systems such as batteries on small scale and the Power-to-Gas system will be of increasing importance in the near future (Deutsche Energie-Agentur (DENA) 2012). For the year 2009, only pump storage is considered in the EMM. For the 2020 and 2030 scenarios, the pump storage capacities are assumed to remain on 2009 levels. For the present study, no other electricity storage systems are examined since reliable scenario data is not available. Other storage systems, however, can be implemented additionally into the EMM if required.

This section develops a high time resolution approach to account for the impact of electricity storage systems of an electricity market.

In the EMM, storage systems storing-in electricity are treated as consumers. When storing-in electricity the current consumption emissions of this particular hour, is stored-in. For the storing-out, the average emissions of electricity previously stored-in are considered as the storage system production, including the efficiency of the power-to-power conversion.

For the first hour of a simulation year, a minimum "filling" of the pump storage of each country has to be defined since it is impossible to know the "State of Charge" (SOC) at the beginning of the modelling. It is assumed that the starting SOC is of such level that the SOC during modelling never runs below the lowest possible SOC. The following formula describes this criterion:

$$\mathrm{Storage}\ (\mathrm{t}=0) = min\left|\sum_{t=0}^{n} \mathrm{In_t} + \mathrm{Out_t}\right| + SOC_{min}$$

Where:

SOC_{min}	Minimum State-of-Charge
$\mathrm{In_t}$	Amount of electricity stored in at time t
$\mathrm{Out_t}$	Amount of electricity stored out at time t

This formula assures that the storage of each country never runs below its minimum SOC. At the same time, the initial content of electricity already in the storage is as low as possible. This is crucial to ensure an unbiased implementation of electricity storage systems in a LCA of electricity consumption. A second assumption is that the initial amount a storage system is filled with is attributed by the annual average of the consumption emissions. Table 4-6 displays a fictive example of the methodology to quantify the impact of storage systems on the LCI of electricity consumption.

Table 4-6: Example Calculation on Electricity Storage

Hour	Sum of Net Storage [kWh]	Sum of CO_2 Storage [kg CO_2-e]	Relative CO_2 Emissions of Storage [kg CO_2-e/kWh]	Relative CO_2 Emissions of Current Consumption Mix [kg CO_2-e/kWh]	Storage in [kWh]	Storage out [kWh]
0	3	1.37	0.46	n.a.	n.a.	n.a.
1	3	1.37	0.46	0.50	0	1
2	2	0.91	0.46	0.40	3	0
3	4.55	2.11	0.42	0.50	0	1
4	4	1.69	0.42	0.60	0	2
5	2	0.84	0.42	0.50	0	0
..						

As shown in the table above the initial filling of the storage at "0" h is three kWh at relative emissions of 0.46 kg CO_2/kWh. During the first hour one kWh of electricity is stored out attributed with 0.46 kg CO_2/kWh. Hence, the pump storage appears as a producer (power plant) in the EMM production. For the second hour three kWh of electricity (gross) are stored in. Now the pump storage appears as a consumer in the EMM, withdrawing three kWh from the electricity market. Hence, the consumed amount of CO_2 is added up (3 kWh * 0.4 kg CO2/ kWh = 1.2 kg CO_2) to the already stored CO_2 emissions. The EMM assumes an efficiency of 80% (Alstorm 2010) of the power-to-power conversion for pump storage. Therefore, the net electricity stored amounts to 4.55 kWh. Now the pump storage can be implemented into the EMM.

4.8 Implementation of the EMM into Data Processing Software

After defining the theoretical and mathematical outline, the interface EMM between power plant data, load data and electricity trade data can be created. The basic structure of the EMM is shown in Figure 4-25

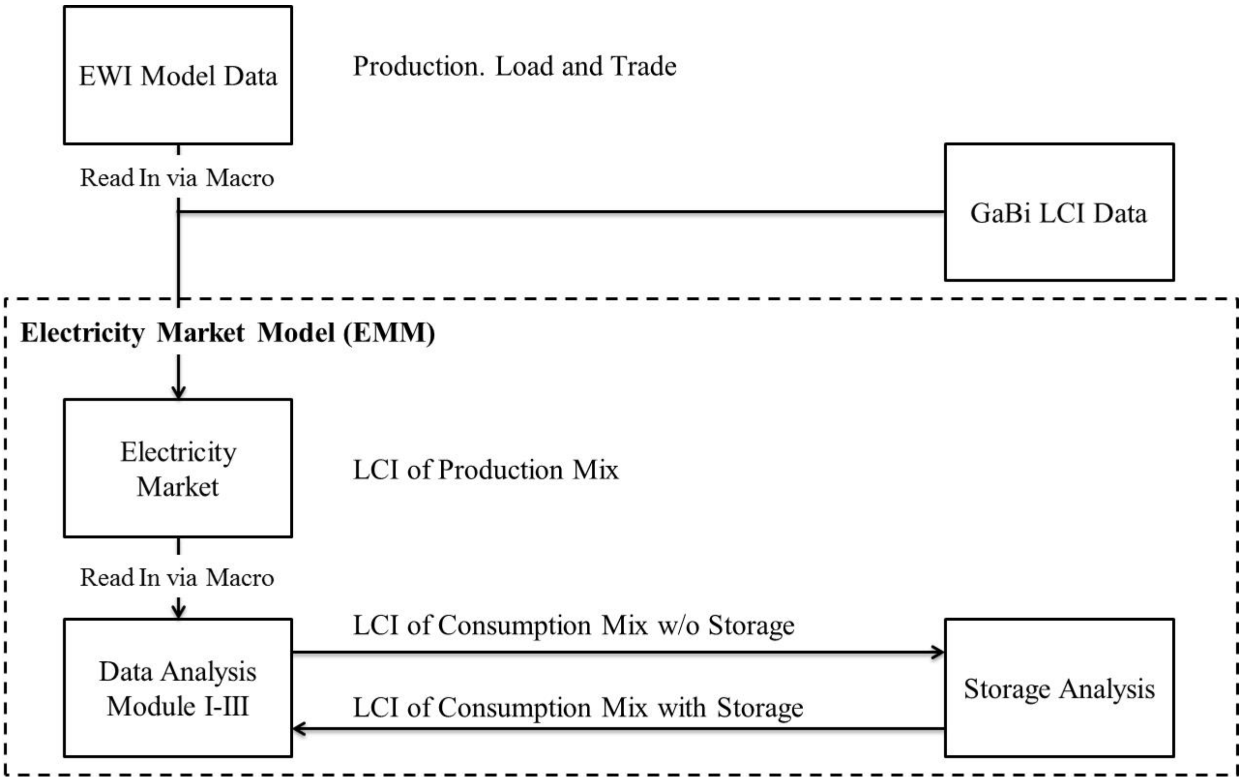

Figure 4-25: The File Structure of the EMM

The DIMENSION Model (EWI 2011) data template consists of an hourly data series of electricity production, electricity demand and physical electricity trade for each of the modelled countries. This template is transferred into the EMM. This is comparable to the loading of a CD-ROM where scenarios can be loaded into the model in order to assess different scenarios quickly. The EMM itself consists of three separate files. The file "Electricity Market" contains LCI data of the power plants. Combined with the DIMENSION Model (EWI 2011) power plant data an LCI of the production mix of each country is calculated.

In order to assess the consumption mix, the Leontief Matrix calculation routine (see Chapter 4.3) starts and creates a new file called "Data Analysis Module I-III". There, the LCI of the consumption mix is calculated. When storing-in, electricity storage systems appear as electricity consumers. When storing-out, the storage systems are treated as electricity producers influencing the LCI of the consumption mix. Accordingly, this step is an iterative approach where the storage data is evaluated separately.

In the following chapters, the results for the application of the EMM are analysed using 2009 data. Furthermore, two scenarios for the year 2020 and 2030 are evaluated.

5. Modelling Results

As described in Chapter 3 Europe is the geographical focus of this study. European countries can differ significantly with regard to their electricity production mix and trade characteristics. The European Network of Transmission System Operators for Electricity (ENTSO-E) is an association of Europe's transmission system operators and in order to provide a holistic approach, the most important European countries of the ENTSO-E network, with regard to electricity production, are chosen for analysis. Each of the countries modelled receives an index for the calculation using the Leontief Matrix as depicted in Figure 5-1.

i=	Country	Country Code ISO 3166 A2
1	Austria	AT
2	Belgium	BE
3	Switzerland	CH
4	Czech Republic	CZ
5	Germany	DE
6	Denmark	DK
7	Spain	ES
8	Finland	FI
9	France	FR
10	Great Britain	GB
11	Ireland	IE
12	Italia	IT
13	Liechtenstein	LI
14	Luxembourg	LU
15	The Netherlands	NL
16	Norway	NO
17	Poland	PL
18	Sweden	SE

Figure 5-1: Countries Modelled and Country Codes (ISO 3166-2 2007)

The most extensive LCA database publicly available is GaBi (PE International 2013) covering all relevant LCI data on every type of power plant in Europe. In this study, the global warming potential" (GWP) on a 100-year basis (GWP 100), the acidification potential (AP), the eutrophication potential (EP) and the photochemical ozone creation potential (POCP) as defined in ReCiPe (GOEDKOOP, M. et al 2009) are assessed in detail. Chapter 5.1 describes the results for the year 2009 with regard to the impact categories GWP 100, AP, EP and POCP. In Chapter 5.2 the results for the years 2020 and 2030 are discussed for GWP 100 and Appendix C provides the 2020 and 2030 figures, respectively.

The following chapter compares the results of the high time resolution approach with the most common current approach of annual averages for Europe. The evaluation of the results bases on the quantification of the possible error a LCA practitioner can make by using annual values. This assessment includes the current (2009) situation (Chapter 0) and scenarios for the years 2020 and 2030 (Chapter 0 and 0) in order to identify future developments and challenges.

5.1 Europe 2009

The main input data for the modelling of the year 2009 is described in Chapter 4.1. In the following chapter, the results of the DIMENSION simulation and the application of the EMM for the year 2009 are evaluated systematically.

5.1.1 From the LCI of the Production Mix to the LCI of the Consumption Mix

5.1.1.1 Greenhouse Gas Emissions

Electricity production characteristics amongst the eighteen European countries vary significantly. France, for instance, relied almost entirely on nuclear power in 2009 whereas Norway could cover almost 100% of the electricity demand by water power (Eurostat 2013). Some countries produce electricity using a wide range of different sources. Some electricity sources such as nuclear or coal are constantly available and whereas others are only seasonally available such as waterpower from reservoirs. Some others are highly variable over a short term such as wind power and solar power. Because of such a diverse electricity production, the CO_2 emissions can vary significantly within a short period of time.

Figure 5-2 depicts the highest possible deviations from an annual average over the course of a year. The light grey bars indicate the positive deviation with a value higher than the annual average and the dark grey bars indicate the negative deviation with a value lower than the annual average. The line represents the maximum error possible when using annual CO_2 values. It has to be noted that the hourly values are annual averages. Therefore, the highest possible error in this case occurs if an application is used 365 days a year for one hour at the same time each day.

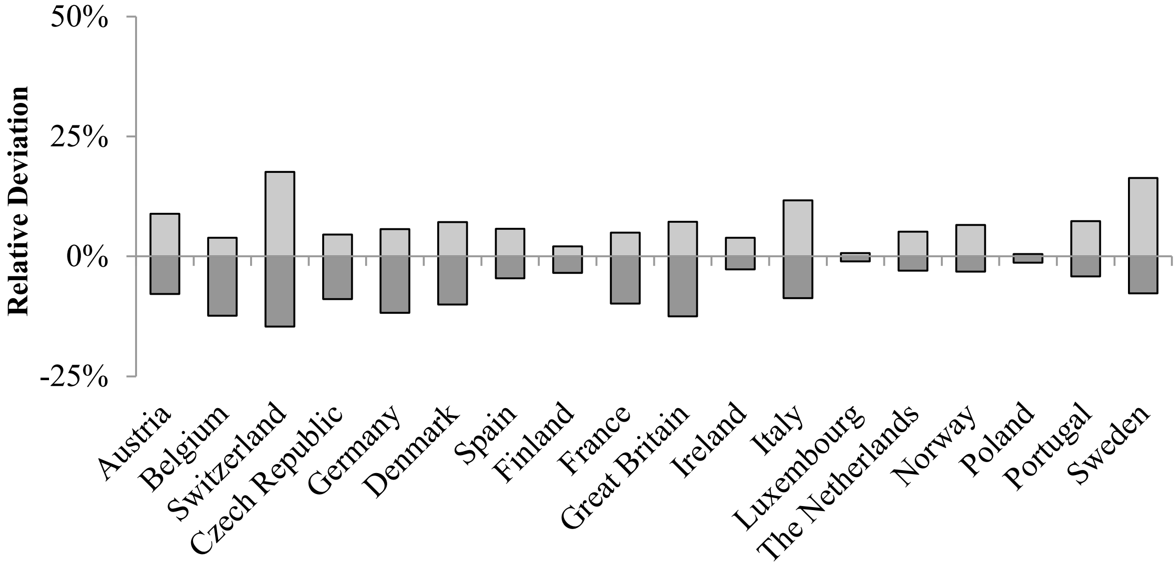

Figure 5-2: Upper and Lower Deviation of the Average GHG Emissions of Electricity Production of the Eighteen European Countries for the Year 2009

The most variable production emissions are identified for Switzerland. At the same time, Swiss electricity production is generally associated with very few GHG emissions. The annual average is calculated to be at 0.035 kg $CO_{2\text{-}e}$/kWh compared to an average of all eighteen countries at 0.410 kg $CO_{2\text{-}e}$/kWh. This is because nuclear power plants and water power plants, which are both very low in CO_2 emissions, mainly produce Swiss electricity. There are two basic types of water power plants featured in this study: Run-of-river water power plants that usually produce constantly over a longer period of time unless a drought or other events take place and water reservoir power plants, which generally produce on demand given enough water is available. Since the profit of each power plant is optimised, the water reservoirs usually produce during times of high electricity prices during peak demand. In case of Switzerland, the additional electricity production of water reservoir power plants decreases the overall average of GHG production emissions. The minimal annual average on an hourly base is around -20% (during peak hours) and the maximum is at 25% (during off-peak hours). Thus, the highest error possible is at around 40%. For a more detailed insight, see Figure 5-3 showing the seasonal situation for Switzerland.

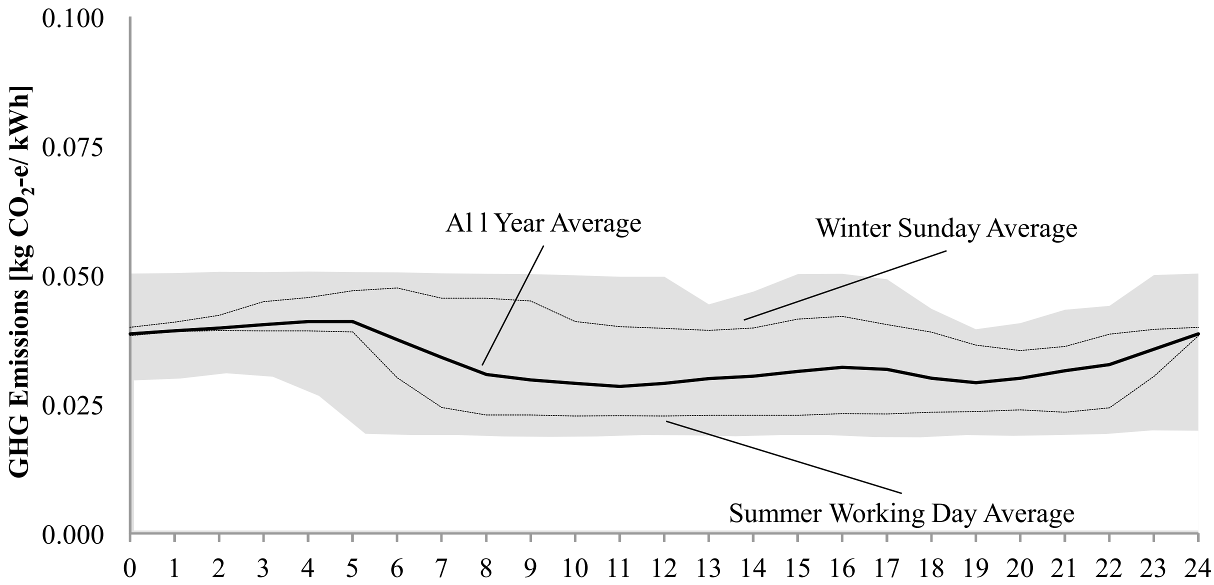

Figure 5-3: Seasonal and Hourly Variations of the GHG Emissions of Electricity Production in Switzerland for the Year 2009

The grey shaded area represents the range of electricity production emissions occurring at least once over the course of a year. The lowest value is around 0.023 kg $CO_{2\text{-}e}$/kWh and the highest is at 0.050 kg $CO_{2\text{-}e}$/kWh. During times of high electricity demand, such as typical working days, the GHG emissions of electricity production in Switzerland are lower since more electricity is produced by renewable sources being mainly reservoir water power plants.

Other countries with a highly variable electricity production profile are for instance Italy and Sweden. Both countries show a strong variation in terms of their use of fossil power plants. Those variations are not discussed since the goal of this study is to examine the general impact of a high-resolution system on LCA rather than to explain the mechanisms behind the electricity production.

As already stated in Chapter 2.3, electricity trade can have a significant effect on the electricity consumption emissions of a country since emissions are imported indirectly when electricity is purchased from another country. The EMM enables the user to analyse hourly (physical) trade data and by applying the procedure described in Chapter 4.2. the electricity consumption emissions including pump storage can be computed additionally. As a result, Figure 5-4 depicts the impact of the electricity import for all eighteen countries on GHG emissions.

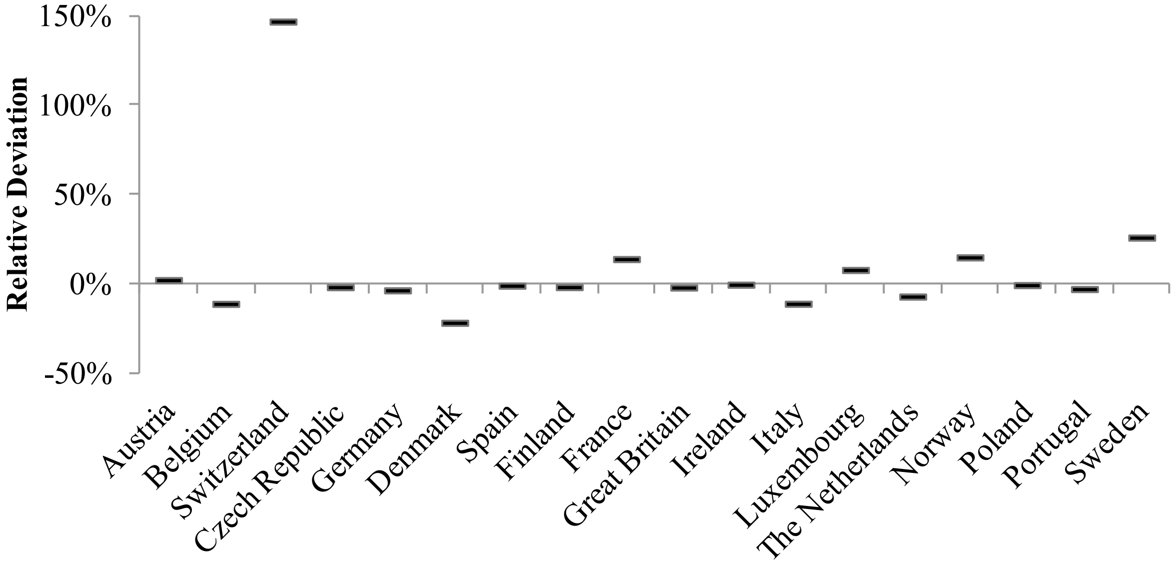

Figure 5-4: Difference between GHG Emissions of Electricity Production and Electricity Consumption for all Eighteen European Countries for the Year 2009

The lines for each country represent the difference between annual values of GHG emissions of the electricity production and the GHG emissions of electricity consumption. Deviations below 0% such as for Denmark (-25%) means that Denmark is reducing the emissions of electricity consumption through trade. On the other hand, Sweden increases the GHG emissions of electricity consumption through trade by 25%.

Generally, two factors strongly influence the impact of electricity trade on consumption emissions: on the one hand, the amount of electricity imported, on the other hand the difference of specific production GHG emissions of the trade partners. This is very relevant for Switzerland, France, Sweden and Norway, which are among the countries with the lowest electricity production CO_2 emissions in Europe. These countries import significant amounts of electricity from neighbouring countries, where electricity production is associated with high GHG emissions (e.g. France and Switzerland are each importing from Germany). Vice versa for Italy, which is importing considerable amounts of electricity from Switzerland, the electricity consumption emissions are lower than the electricity production emissions. Figure 5-5 depicts the variations of the GHG electricity consumption emissions for all eighteen European countries.

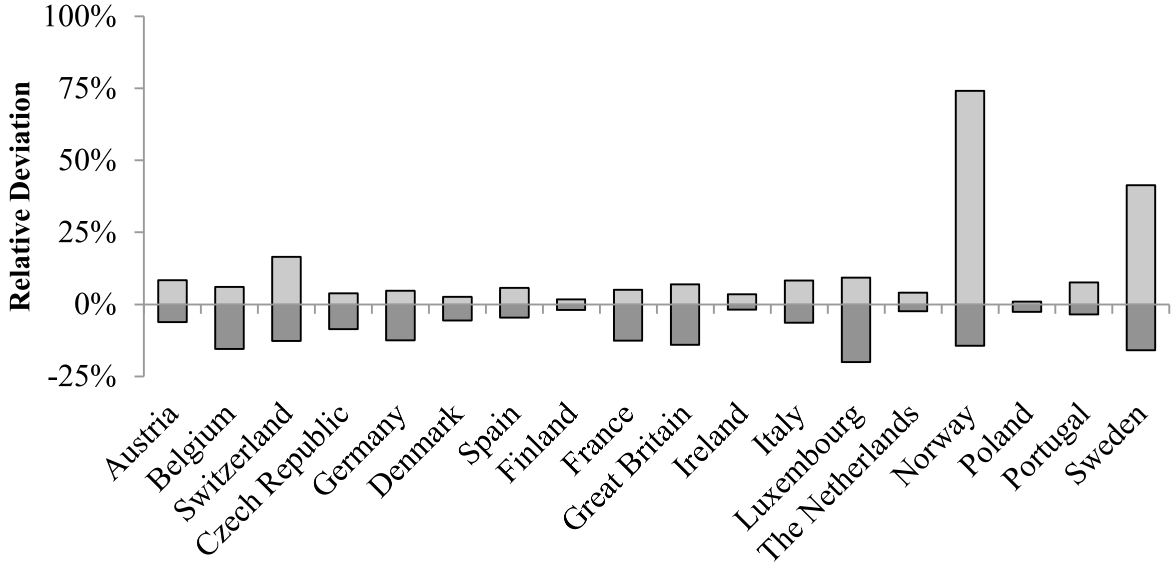

Figure 5-5: **Upper and Lower Deviation of the Average GHG Emissions of Electricity Consumption for all Eighteen European Countries for the Year 2009**

Here, the highest impact shows again for electricity producers with low GHG emissions such as Norway, Sweden and Switzerland. Since the deviations are the highest for Norway, the pattern for Norway is depicted in Figure 5-6.

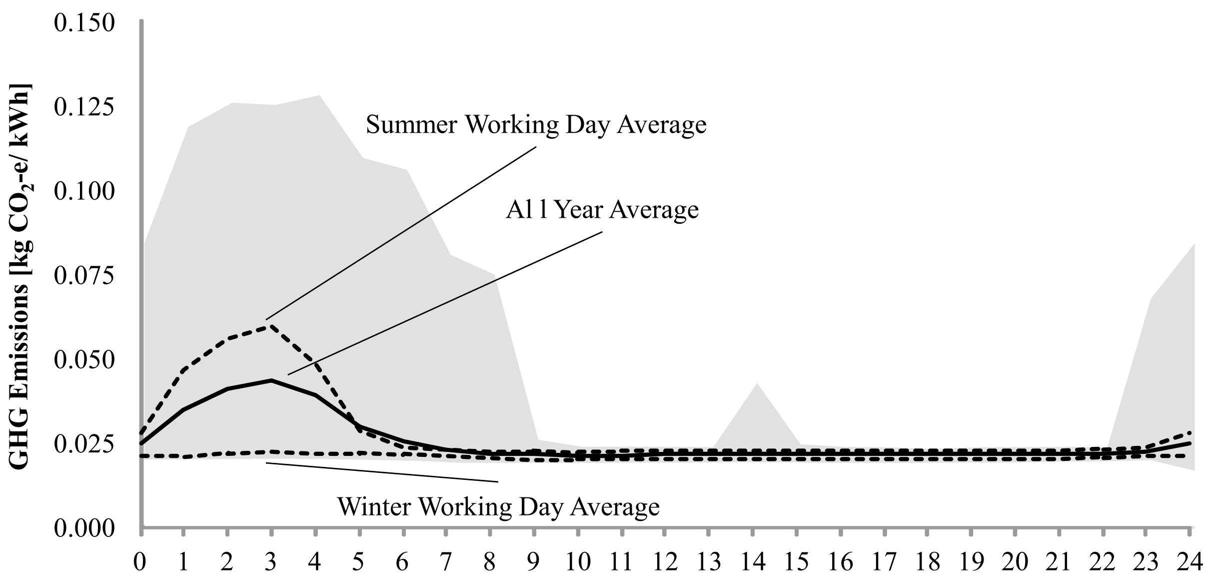

Figure 5-6: **Seasonal and Hourly Variations of the GHG Emissions of Electricity Consumption in Norway for the Year 2009**

Like in the example for Switzerland, in the early hours of the day when demand is low, the water reservoirs are not used to produce electricity in Norway. Instead the electricity needed can be imported cheaply from countries using thermal power plants such as coal. The low electricity price is because it is mostly cheaper for the owner of a coal power plant to sell the electricity discounted than to go down with the production of electricity. In the case of Norway, the Netherlands are selling mainly electricity from coal to Norway at night. Because of that, the difference between lows and highs can be up to 300% for Norway. In winter, the demand is generally higher in Norway since most households use electricity for heating and lighting, both in high demand, resulting in lower emissions during the winter season where more electricity is produced by renewable sources being mainly reservoir water power plants.

5.1.2 Pump Storage

As previously mentioned, the currently available LCA methodologies use assumptions to estimate the impact of pump storage on the electricity consumption emissions of a country. In order to do so, either a country specific electricity consumption mix is used, or a general assumption, using electricity from coal power plants to run the pumps of the storage system (see Chapter 2.5) is applied. Using a high time resolution, however, enables a very detailed insight into whether the pump storage application is either storing-in or storing-out; therefore, a more precise analysis of the environmental impacts of electricity consumption is possible. Figure 5-7 depicts the difference between the annual consumption GHG emissions and the average store-out emissions indicating the error made when using annual averages by estimating the impact of storage systems for countries with pump storage.

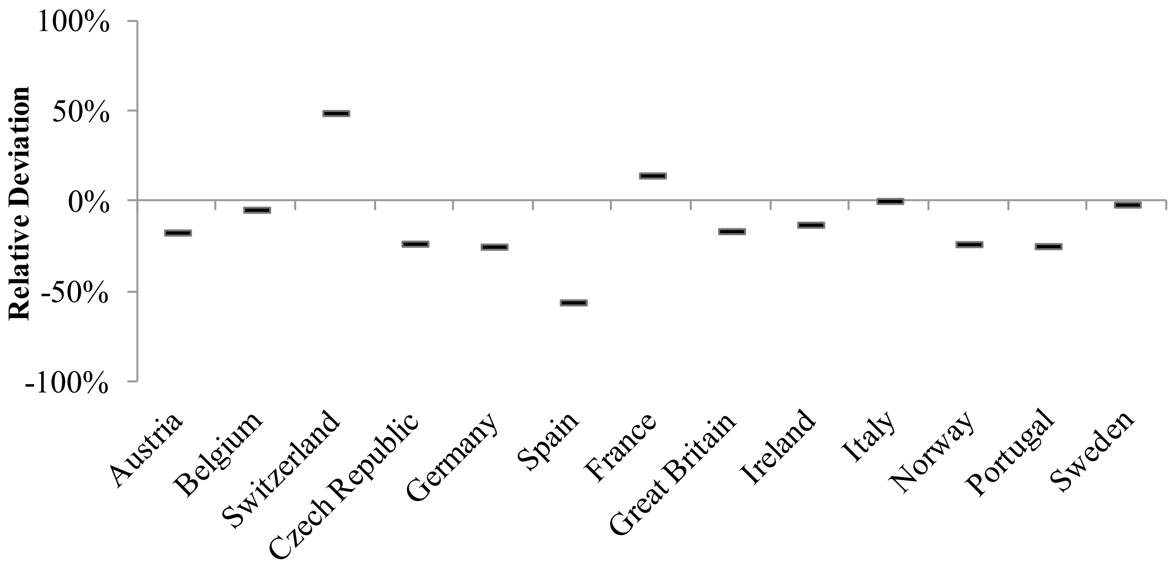

Figure 5-7: Relative Deviation of GHG Emissions of Electricity Production of Pump Storage Compared to GHG Emissions of Electricity Consumption in Countries with Pump Storage for the Year 2009

For most of the countries, the average store-in is performing better than the annual average in terms of GHG emission. This is because most renewables do not require costly fuels reducing electricity generation cost and thus market prices significantly. An owner of a storage system is always trying to maximise profits and is therefore storing-in when electricity is cheap. This is mostly the case for a high share of renewables. Therefore, more renewable electricity is stored-in through storage systems. The time of storing-out is usually at times when prices are high. The only exception are Switzerland and France where some of the storage capacities are filled with imported electricity that tends to have high electricity consumption GHG emissions.

It has to be noted, however, that the amount of electricity stored through pump storage in Europe is below 0.1% of the production in each country and is therefore not relevant for the final GHG emissions of electricity consumption.

The following chapter presents the results of a direct comparison of the impact categories defined in Chapter 3.

5.1.2.1 Other Impact Categories

5.1.2.1.1 From the Production Mix to the Consumption Mix

Depending on the mix of power plant types in different countries, some impact categories are more relevant than others. Therefore, the four impact categories considered in this study are summarised in Figure 5-8 for comparison.

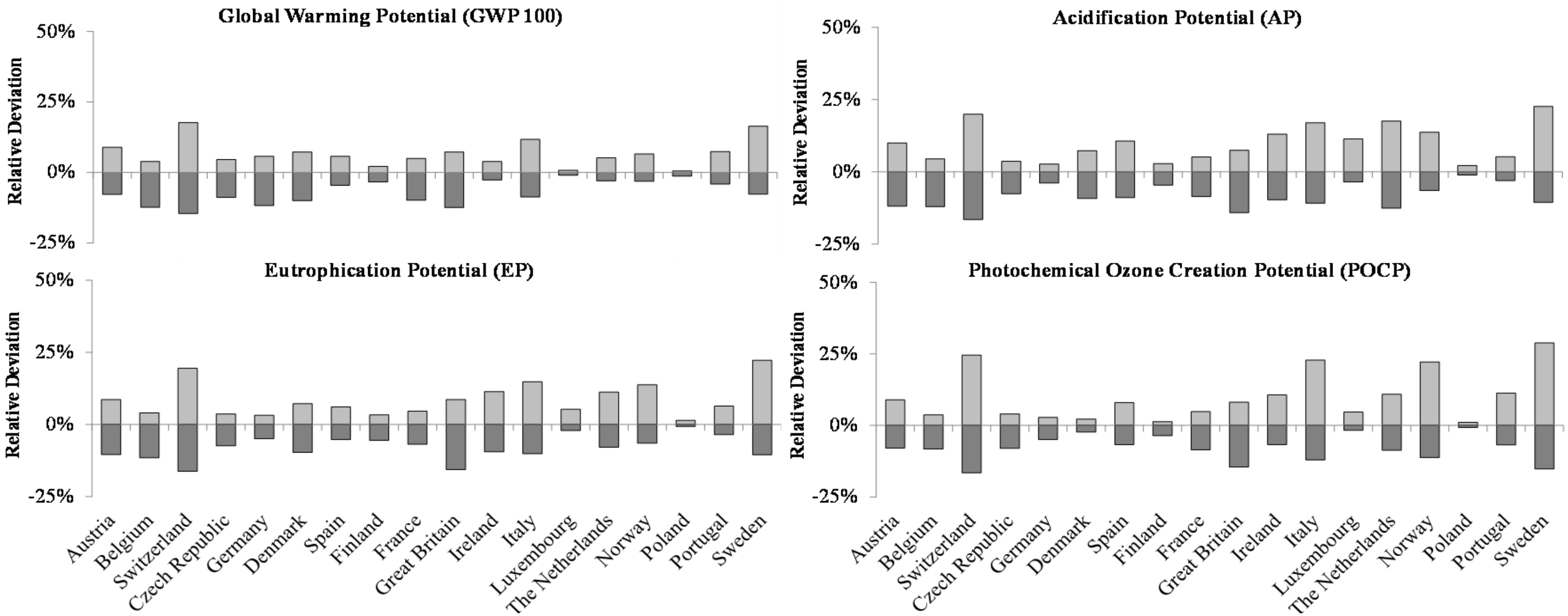

Figure 5-8: Upper and Lower Deviation of the Average GWP, AP, EP and POCP Emissions of Electricity Production for the Eighteen European Countries in 2009

The deviations of the impact categories are in some cases very different. For Italy, for instance, deviations are the highest for POCP (+26% and -14% respectively). This is mainly due to the relevance of fuel oil power plants for the impact category POCP compared to other power plant types. Fuel oil power plants typically are switched on in times of high demand for a short period of time, hence increasing the overall deviation significantly. In summary, it can be said that the different magnitudes of deviations between different impact categories strongly depend on the relevance of the fluctuating types of power plants in the respective impact category. Fluctuating power plants are typically natural gas and fuel oil due to comparably high fuel costs.

With regard to the impact of direct exchange of electricity, Figure 5-9 depicts the difference between production and electricity consumption emissions for the four impact categories considered.

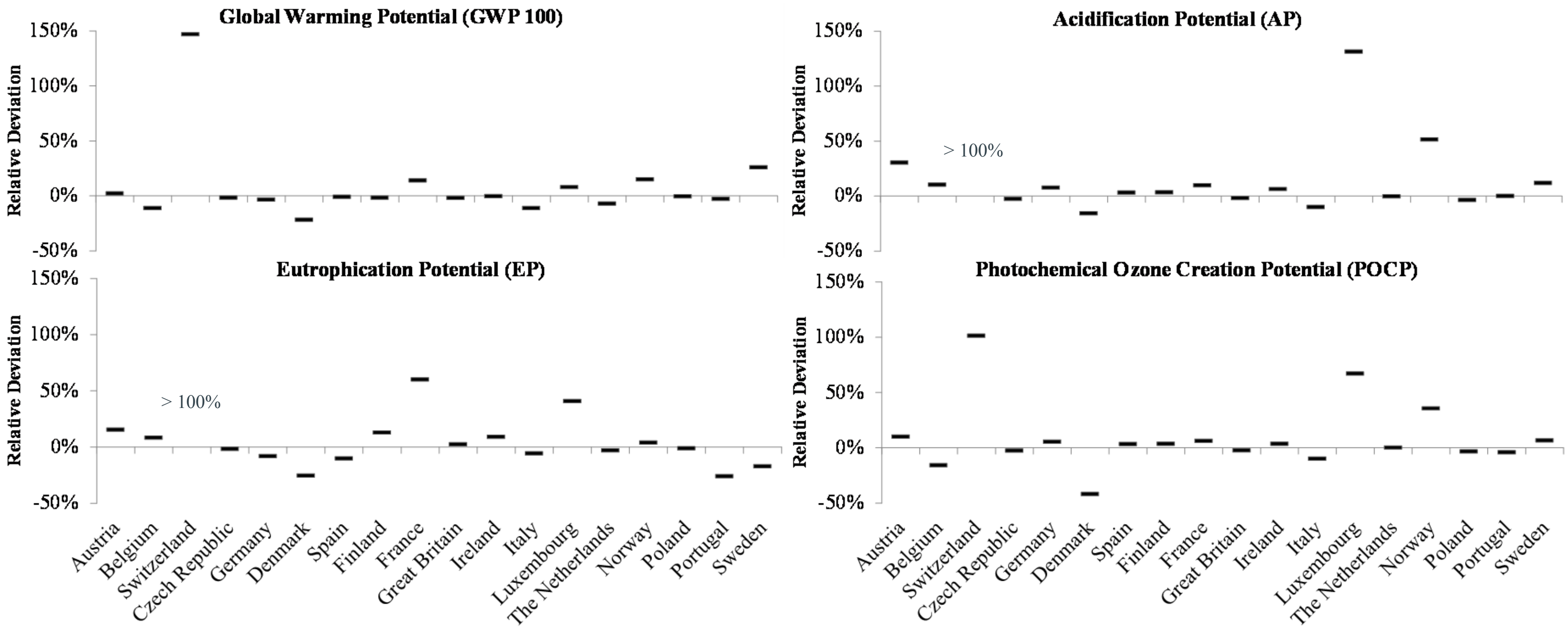

Figure 5-9: Difference between Production and Electricity Consumption GWP, AP, EP and POCP Emissions for all Eighteen European Countries for the Year 2009

The relevance of trade is mainly defined by two factors: First, the relevance of the impact category of the country the electricity is imported from compared to the relevance of the impact category in the country itself. Secondly, the share of the imported electricity for consumption. An extreme example are AP emissions for the small country Luxembourg that imports significant amounts of electricity from Belgium and Germany. Both countries rely on electricity from coal power plants of which some is exported. Luxembourg itself is has very low AP emissions and therefore the impact of trade on the AP is the highest of all impact categories at almost 150% difference between production and consumption emissions.

The most relevant information from a LCA point of view is that on consumption emissions. Hence, Figure 5-10 shows the electricity consumption emissions for the four impact categories considered

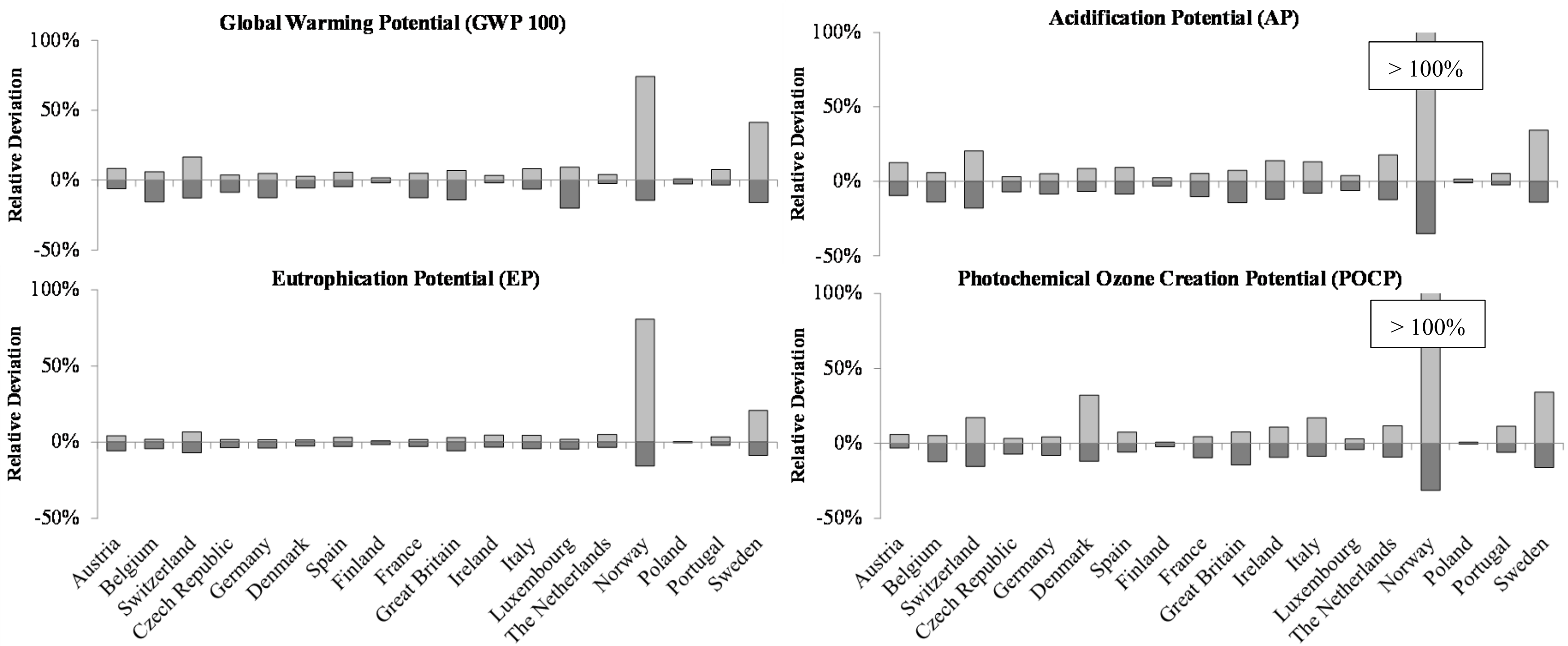

Figure 5-10: Upper and Lower Deviation of the Average AP, EP and POCP Emissions of Electricity Consumption for the Eighteen European Countries in 2009

It is worth noting that the trade of electricity causes severe deviations for Norway. This is because Norway has generally low emissions associated with electricity production as most of the electricity is produced by waterpower. When importing from countries with a high share of electricity generated by fossil sources, electricity consumption emissions rise significantly. Norway is therefore the country with the highest deviations for all impact categories.

With the evaluation of production and the consumption emissions, the hybrid function of electric storage systems as producers and consumers can be discussed in the following chapter.

5.1.2.1.2 Electricity Storage Systems

One of the most distinctive features of the EMM is its capacity to implement electricity storage systems. Electricity storage systems can act as electricity consumers as well as electricity producers. Figure 5-11 shows the relative deviation of AP, EP and POCP of electricity production of pump storage compared to electricity consumption emissions.

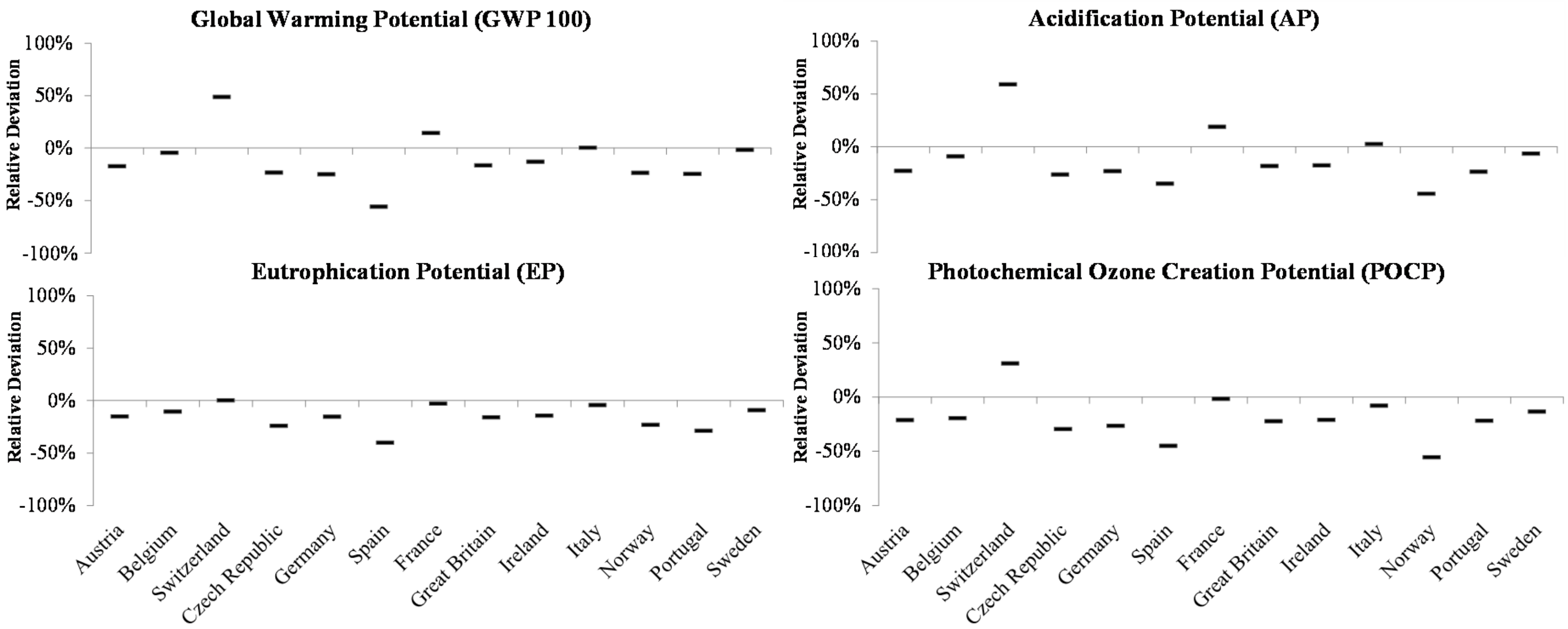

Figure 5-11: Relative Deviation of AP, EP and POCP of Electricity Production of Pump Storage Compared to AP, EP and POCP Emissions of Electricity Consumption in Countries with Pump Storage for the Year 2009

For most of the countries, the average store-in is performing better than the annual average consumption emissions similar to the GHG emission described in Chapter 5.1.2. For Switzerland the results for the EP differs from other impact categories. This is because Switzerland is storing in imported electricity with lower EP emissions compared to other impact categories.

In order to identify the future relevance of a high-resolution LCA approach for the future, the following chapters present an outlook to the years 2020 and 2030, respectively.

5.2 Scenarios for Europe 2020 and 2030

An important aspect of this study is the assessment of how future developments of the European electricity market influence the LCA of electricity consumption. In order to do so, the assumptions for the years 2020 and 2030 have to be defined before running a simulation with the DIMENSION Model (FÜRSCH, M. et al 2011). These assumptions are described in the following chapter.

5.2.1 Assumptions

The most important assumption is the development of the installed capacity of renewable energy systems. In Table 5-1 the aggregated capacities of renewables in Europe for the years 2009, 2020 and 2030 is listed. For the full list of assumptions for each country, see Appendix A.

Table 5-1: Installed Capacities of Renewables in Europe for the Years 2009, 2020 and 2030 DIMENSION Model Simulation (Beurskens L. W. M. et al. 2011), (European Climate Foundation's (ECF) 2011), (Organisation for Economic Co-operation and Development (OECD) 2010) and (FÜRSCH, M. et al 2011)

Technology	Capacity [GW] 2009	Capacity [GW] 2020	Capacity [GW] 2030
Wind (Onshore and Offshore)	73.5	212.6	291.7
Photovoltaic	15.8	80.9	103.9
Hydropower (Water Reservoir)	92.4	90.6	90.6
Hydropower (Run-of-River)	37.2	37.2	37.2
Biogas	5.0	10.3	12.7
Biomass	13.5	30.0	34.6
Geothermal	1.5	1.5	1.8

Further important assumptions are fuel prices and the CO_2 emission certificate prices as listed in Table 5-2.

Table 5-2: Fuel and CO_2 Certificate Prices for the Years 2020 and 2030 (Organisation for Economic Co-operation and Development (OECD) 2010) and (Curran M. A. et al. 2005)

	2020	2030
Uranium [$€_{2010}/MWh_{TH}$]	3.3	3.3
Lignite [$€_{2010}/MWh_{TH}$]	1.4	1.4
Hard Coal [$€_{2010}/MWh_{TH}$]	13.4	13.8
Natural Gas [$€_{2010}/MWh_{TH}$]	28.1	31.3
Fuel Oil [$€_{2010}/MWh_{TH}$]	99.0	110.0
CO_2 Certificate Prices [$€_{2010}/t$]	22.7	30.2

For weather dependent applications such as solar, wind and hydropower, the DIMENSION Model (EWI 2011) uses 2009 meteorological data to maintain consistency with the 2009 results. For weather independent renewable energy source, such as biomass or biogas, the full load hour determined in the 2009 scenario are used. The sum of the weather dependent and the weather independent technologies is the total electricity production from renewable sources. In order to compute the residual load, this electricity production from renewables has to be subtracted from the actual load. The residual load is therefore defined as the difference between demand and the electricity production from renewable sources. By applying this approach, assumptions for the electricity demand are necessary. The electricity demand is constantly increasing in most European countries. For Germany, however, a constant electricity demand is assumed since several studies provide different trends (PIEPRZYK, B. 2012), (BUNDESMINISTERIUM FÜR UMWELT, Naturschutz und Reaktorsicherheit (BMU) 2011), (FAHL, U. et al 2010) and no general proposition can be concluded.

In Table 5-3 the projected net electricity demand of the eighteen European countries for 2020 and 2030 is listed.

Table 5-3: Net Electricity Demand of the Eighteen European Countries for the Years 2020 and 2030 (Capros P. et al. 2010), (BUNDESMINISTERIUM FÜR UMWELT, Naturschutz und Reaktorsicherheit (BMU) 2011), (FAHL, U. et al 2010) and (PIEPRZYK, B. 2012)

Country	Demand 2009 [TWh]	Demand 2020 [TWh]	Demand 2030 [TWh]
Austria	65.6	62.3	70.5
Belgium	84.6	92.9	105.6
Switzerland	63.0	65.4	70.1
Czech Republic	61.6	69.7	79.3
Germany	526.9	535.4	535.4
Denmark	34.0	35.0	39.1
Spain	258.9	297.4	344.4
Finland	80.8	90.2	90.9
France	486.4	482.6	549.7
Great Britain	323.4	365.5	387.2
Ireland	26.2	29.5	35.2
Italy	317.6	345.1	378.0
Luxembourg	6.2	8.0	9.0
Netherlands	112.9	117.9	123.1
Norway	121.6	118.7	127.3
Poland	136.8	138.8	165.3
Portugal	51.4	52.3	59.3
Sweden	138.5	139	143.1

The pattern of the hourly electricity consumption is assumed to be proportional to the 2009 electricity consumption pattern.

Now that the residual load can be computed, the DIMENSION Model (EWI 2011) is able to simulate the installed capacities of fossil power plants by determining the economically most feasible option to install new capacities. The result of this simulation of fossil power plants is listed in Table 5-4.

Table 5-4: Installed Capacities of Thermal Power Plants in Europe for the Years 2020 and 2030 (EWI 2011)

Technology	Capacity [GW] 2009	Capacity [GW] 2020	Capacity [GW] 2030
Nuclear	125.3	100.0	106.9
Hard Coal	126.2	108.4	119.3
Lignite	42.0	39.4	40.2
Natural Gas	217.9	214.6	210.4
Fuel Oil	50.4	37.7	31.6

Furthermore, assumptions for the efficiency of the power plants need to be considered. Since it is almost impossible to estimate the average efficiency of each type of power plant in every European country, it is assumed that the average efficiency increases by 3% between 2009 and 2020 and by another 3% from 2020 to 2030. This is an average increase of efficiencies as shown in (European Environment Agency 2013). The distribution losses as shown in Table 4-2 remain constant throughout all scenarios.

5.2.2 From the LCI of the Production Mix to the LCI of the Consumption Mix

Based on the assumptions described above, the results have been assessed in the same way as for 2009. The focus of the discussion, however, is now on the change of the results with an increasing share of renewables and the implication in terms of LCA results. The results for the Deviation of the Average GHG Emissions of Electricity Production are depicted in Figure 5-12. In contrast to the presentation in Chapter 0, the upper and lower deviation is not shown here. The lines represent the 2009 highest possible deviation for the year 2009 as shown in Figure 5-2. The bars, however, represent the absolute maximum deviation in 2020 (light grey) and 2030 (dark grey).

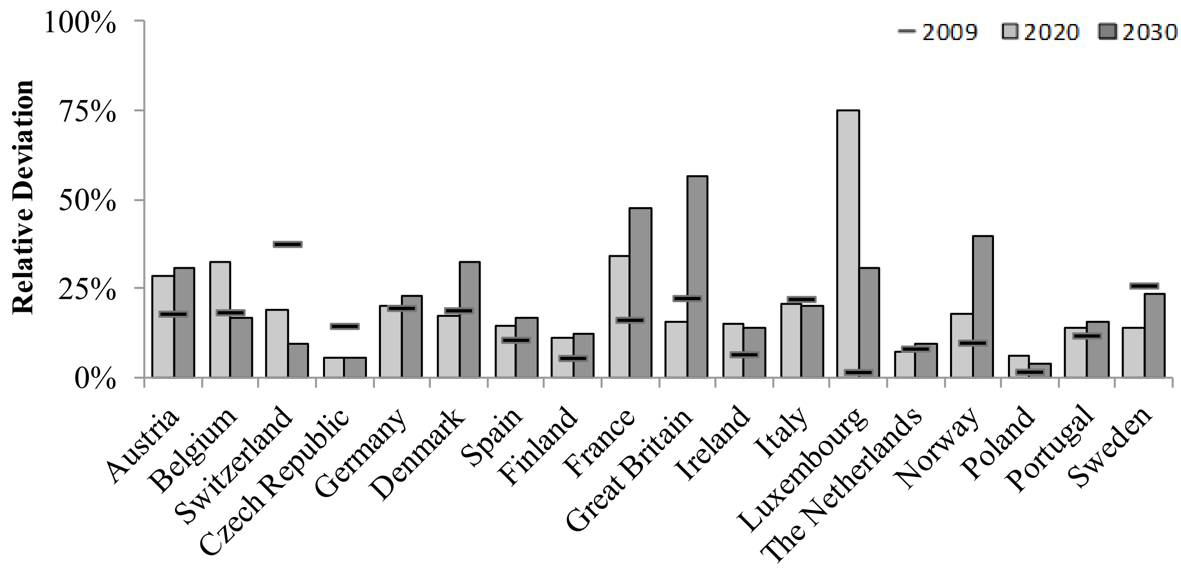

Figure 5-12: Deviation of the Average GHG Emissions of Electricity Production for all Eighteen European Countries for the Years 2009, 2020 and 2030

There is no obvious trend for most of the countries. For some countries, such as Austria and France, however, maximum deviations between annual averages and hourly averages of GHG emissions of electricity production increase significantly. This is because Austria and France are forced to install flexible natural gas power plants to back-up the increasing share of electricity from wind and solar sources. These natural gas power plants produce electricity when little wind is blowing and solar radiation is low and therefore increase deviations to a high degree.

On the other hand, other countries are not affected by growing deviations in 2020 and 2030. There are three explanations for this. First of all, some countries are not increasing their share of renewables, as this share is already high in 2009. Some countries are able to increase the capacity of renewables, which are not, or only to a small extent meteorologically variable, such as biomass power plants or run-of-river power plants. Furthermore, some countries are able to compensate variations in production through trade. The increase of electricity trade within Europe leads to a higher impact of the trade schemes for the LCA of electricity consumption. The amounts of electricity trade increased from 445 TWh in 2009 to 556 TWh in 2020 and 773 TWh in 2030 between all eighteen countries, respectively. Figure 5-13 visualises the difference between electricity production GHG emissions and electricity consumption GHG emissions for all modelled countries for 2009, 2020 and 2030.

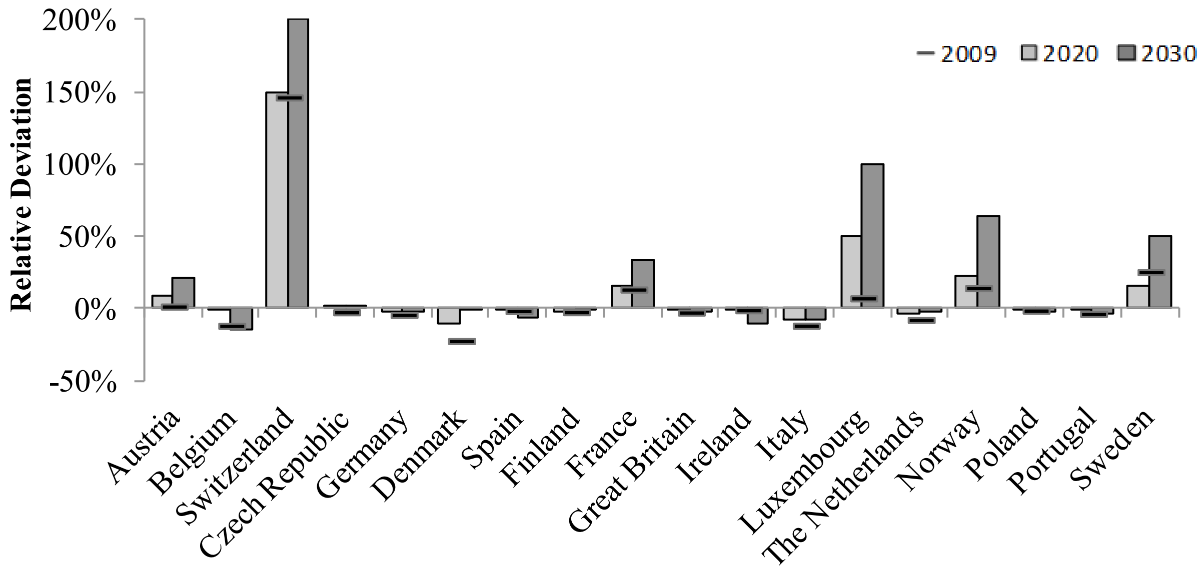

Figure 5-13: Difference between Electricity Production GHG Emissions and Electricity Consumption GHG Emissions for all Eighteen European Countries for the Years 2009, 2020 and 2030

There is a strong impact of trade for some of the countries. This impact increases further with the amount of electricity traded. Especially the smaller countries with a low electricity production are strongly influenced by the trade with their neighbours. Austria and Switzerland for instance are increasingly importing from Germany. This trade can also increase the deviation of the hourly GHG emissions of electricity consumption from the annual average. Figure 5-14 therefore depicts the deviations of electricity consumption GHG emissions for all modelled countries for 2009, 2020 and 2030.

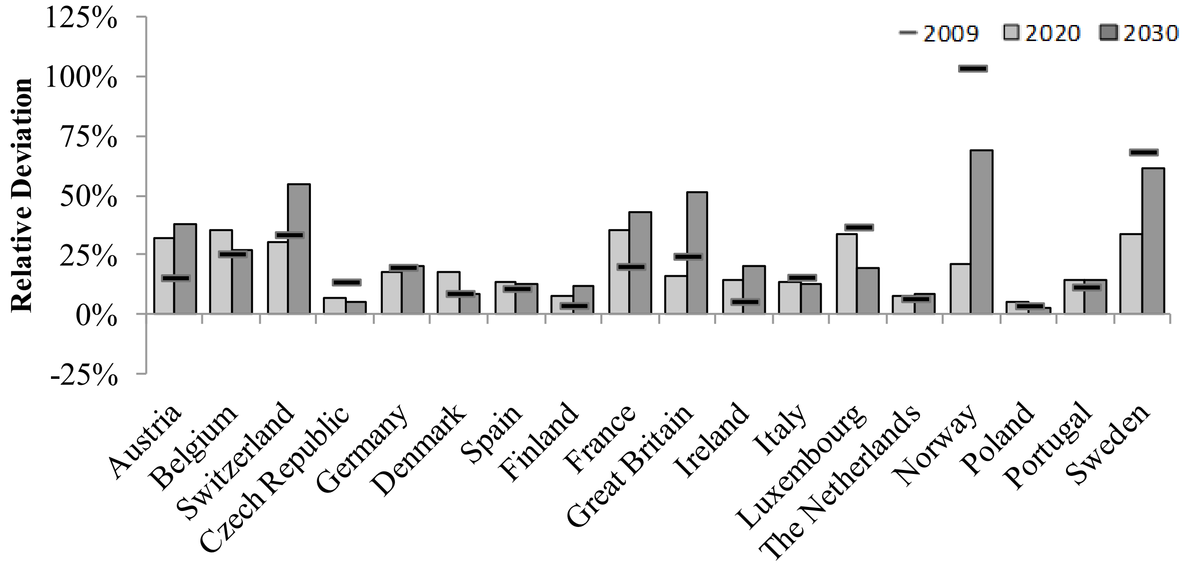

Figure 5-14: Deviations of the GHG Emissions of Electricity Consumption all Modelled Countries for the Years 2009, 2020 and 2030.

There is no obvious trend for most of the countries. For some countries such as Great Britain, Ireland, Austria and France, however, maximum deviations between annual averages and hourly averages of GHG emissions of electricity consumption increase significantly. The deviations of the GHG emissions of the electricity consumption are very heterogeneous throughout Europe and that no general conclusion can be drawn.

Finally, the change over time concerning electricity consumption emissions of pump storage is examined in the following chapter.

5.2.3 Pump Storage

With an increasing share of electricity generated from fluctuating renewable resources, the importance of electricity storage systems is further increasing. Figure 5-15 therefore depicts the impact of future developments on the results for pump storage.

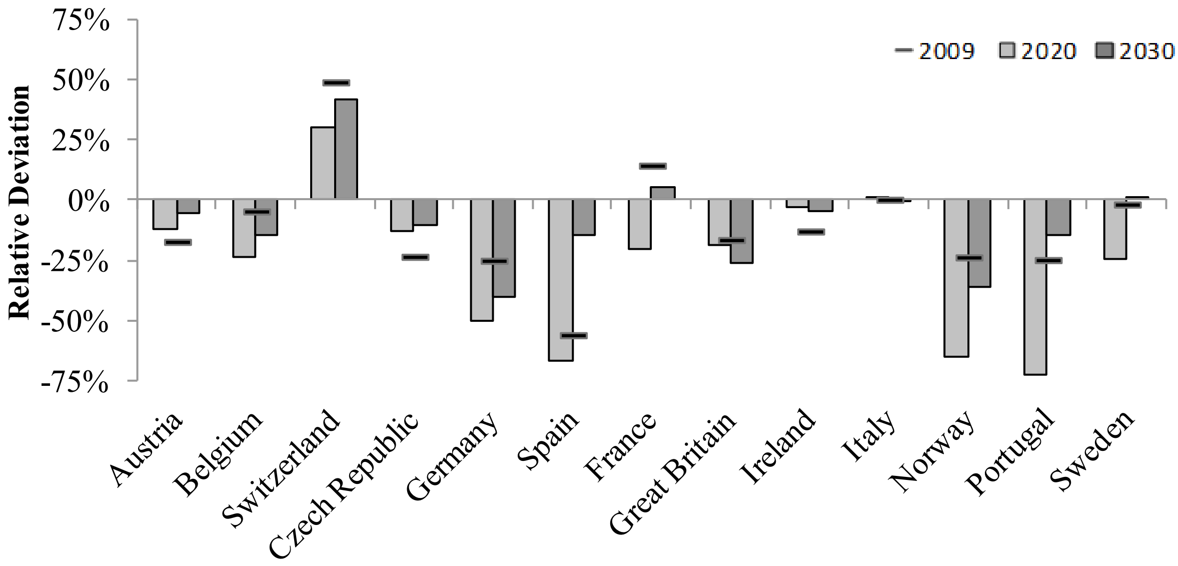

Figure 5-15: GHG Emissions of Electricity Production of Pump Storage in Countries with Pump Storage for the Years 2009, 2020 and 2030

The situation here is heterogeneous as well, as no absolute conclusion can be drawn whether the increase of electricity from renewable sources results in a significant change of GHG emissions from pump storage. In the course of this study small-scale electricity storage applications such as batteries for PV power plants are not examined. The results presented solely give an indication on how to apply the hourly resolution on the pump storage systems, which then can be applied to assess the environmental impact of other storage options.

The following chapter analyses the impact of the implementation of the transit trade and certificate trade on the EMM by introducing Module II and Module III, respectively.

6. The Impact of Electricity Trade and Time Resolution

In this chapter, the impact of the electricity trade is examined. Electricity trade in the study at hand is defined as described in Chapter 4.4. The main objective is to show the differences between the current approach with a low time resolution where transit and virtual trade is either neglected or defined by assumptions and the results of the detailed assessment in the EMM.

6.1 Comparison of Different Trade Models and Different Time Resolutions

As described in Chapter 2, there are different models available to account for electricity trade. Model 1 to Model 4 each considers trade differently. In Model 3, for instance, the impact of imports is the highest whereas Model 1 does not account for imports at all. In order to compare the results adequately, all four models are applied to the EMM results on an annual time resolution. Additionally, the results of the EMM for each annual time resolution as well as an hourly time resolution are examined for further comparison. Figure 6-1 depicts the differences of the models using Switzerland as an example.

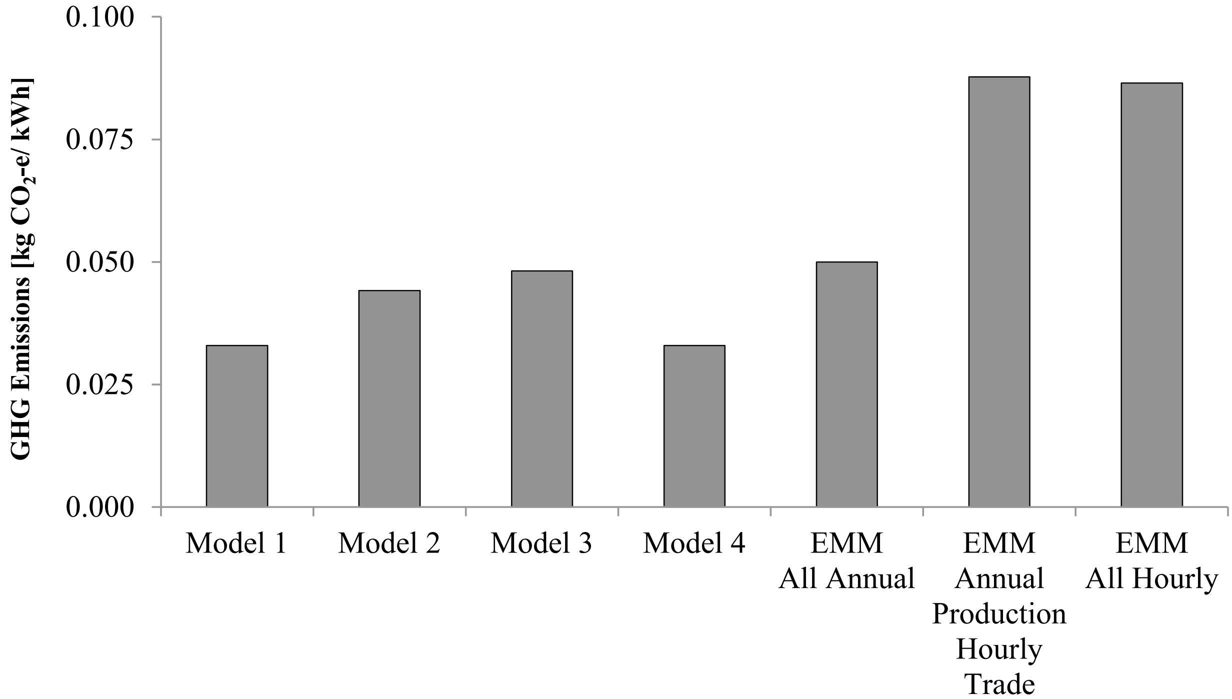

Figure 6-1: Trade Model Comparison for Switzerland in 2009

Since Model 1 does not account for trade, the results shown here represent the emissions of the electricity production in Switzerland. For both Model 2 and Model 3 trade changes the annual average of the electricity consumption significantly compared to Model 1. Since only net trade is accounted for, the results for Model 4 indicate a lower significance of trade. The EMM (annual) approach is the closest, slightly below the results of Model 3. If a high time resolution approach for the EEM is performed, the GHG emissions of electricity consumption increase significantly for Switzerland. This is because an annual trade balance does not account for short term variations. An annual balance of zero can mean either one unit is traded each way or a million units are traded each way. Since electricity cannot be stored in the grid, it is either one unit consumed or a million units consumed over the course of a year. In case of Switzerland, there is a high amount of electricity trade with Germany both ways. Exporting electricity will not change the relative LCI of electricity consumption for Switzerland. However, Switzerland also imports considerable amounts of electricity from Germany changing the LCI of electricity consumption dramatically. The usage of an annual balance of electricity trade can therefore lead to significant errors. Figure 6-2 visualises the difference for each of the eighteen European countries in comparison with their respective annual balance data for the EEM.

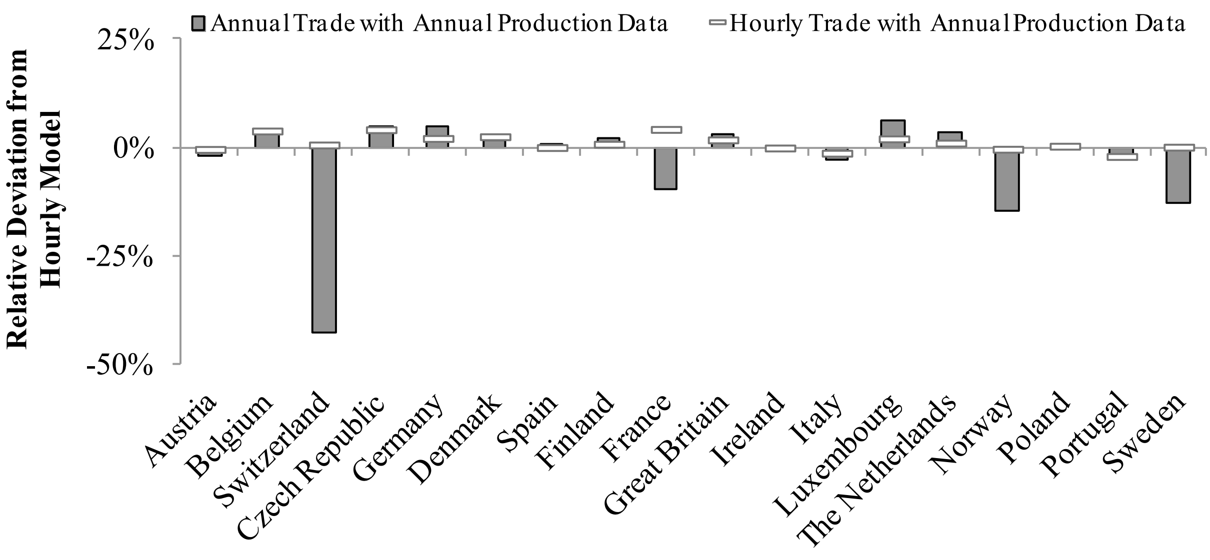

Figure 6-2: Hourly Trade vs. Annual Trade Comparison for GHG Electricity Consumption Emissions in Europe for the Year 2009

For Switzerland the error is the most significant. Using only annual trades balance, leads to an underestimation of imports and GHG emissions of the electricity consumption. By using the high-resolution approach for electricity production and trade, these are almost 50% higher! The error then reduced to less than 1% if high-resolution trade data is used. The usage of high-resolution trade data is therefore way more effective than high-resolution electricity production data.

Figure 6-3 depicts the absolute values for the miscalculation of each model in comparison to the high-resolution model.

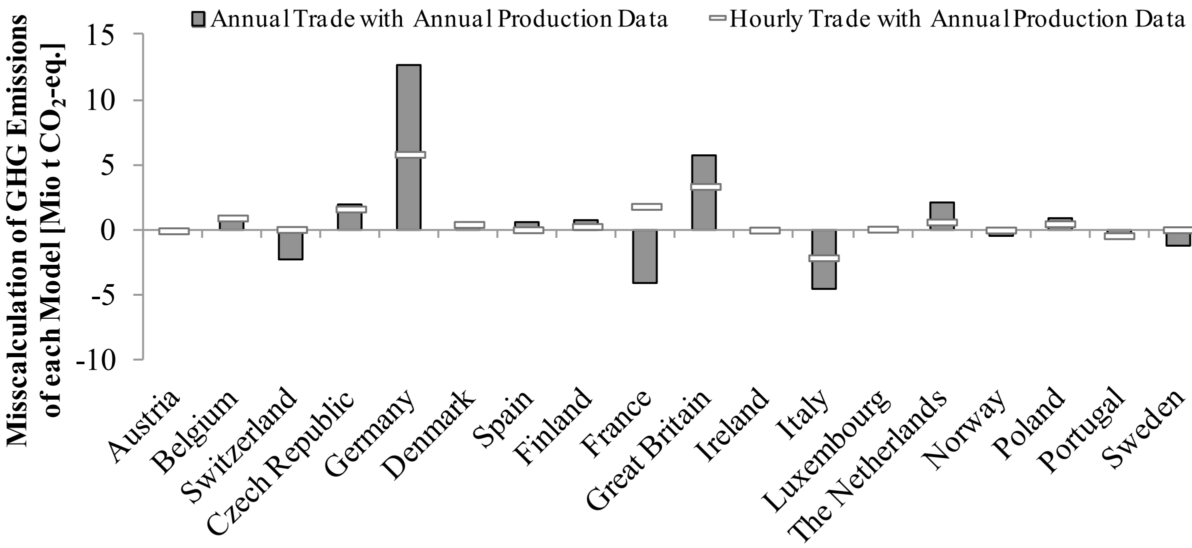

Figure 6-3: Quantification of Absolute Miscalculations Hourly Trade vs. Annual Trade Comparison for GHG Electricity Consumption Emissions in Europe for the Year 2009

The absolute miscalculation is the highest for Germany. Germany is the biggest producer and consumer in Europe and produces electricity with relatively high GHG emissions. Therefore, a small relative miscalculation of 2% - 4% can lead to high absolute calculation errors of 5 Mt – 14 Mt of GHG emissions, respectively. The miscalculations for most European countries are also significant. Hence, it is of crucial importance to accurately account for electricity consumption emissions.

It can be concluded that an analysis of hourly trade data when assessing the LCI of electricity consumption increases accuracy. Although data availability is an issue it is noted that electricity trade data is available up to a 15 minute resolution at (SwissGrid AG 2012b). Using high-resolution trade data with annual average values for electricity production can significantly reduce errors.

6.2 Transit Trade

As described in Chapter 4.4, transit trade can be accounted for if reliable data is available. There is no universal database available covering all data on transit trade. At the time this study is prepared, dynamics of the European electricity market become gradually more transparent. Part of this development are for example grid providers such as SwissGrid that started to publish detailed data on transit trade for their territory. Based on this detailed information, in this chapter the demonstration of Module II of the EMM uses Switzerland as an example.

Switzerland is a typical electricity transiting country (MÉNARD, M. et al. 1998) and (SwissGrid AG 2012a). A significant amount of electricity purchased by Italy from e.g. Germany is transmitted through the Swiss grid. However, the current methodology does not account for the transmission of German electricity to Italy but accounts only for the Swiss consumption mix. Since this electricity is only transmitted, the emissions of German electricity have to be allocated to the final customer Italy. Swiss Grid defines transit electricity as electricity that is imported and not used by Switzerland within 15 minutes. If within 15 minutes more electricity is imported than exported, the electricity not consumed is considered as transited electricity. An assumption of the proportional share for each importing country is used. Figure 6-4 depicts the annual transit electricity flows through Switzerland in 2009 by the country of origin (below) and the destination country.

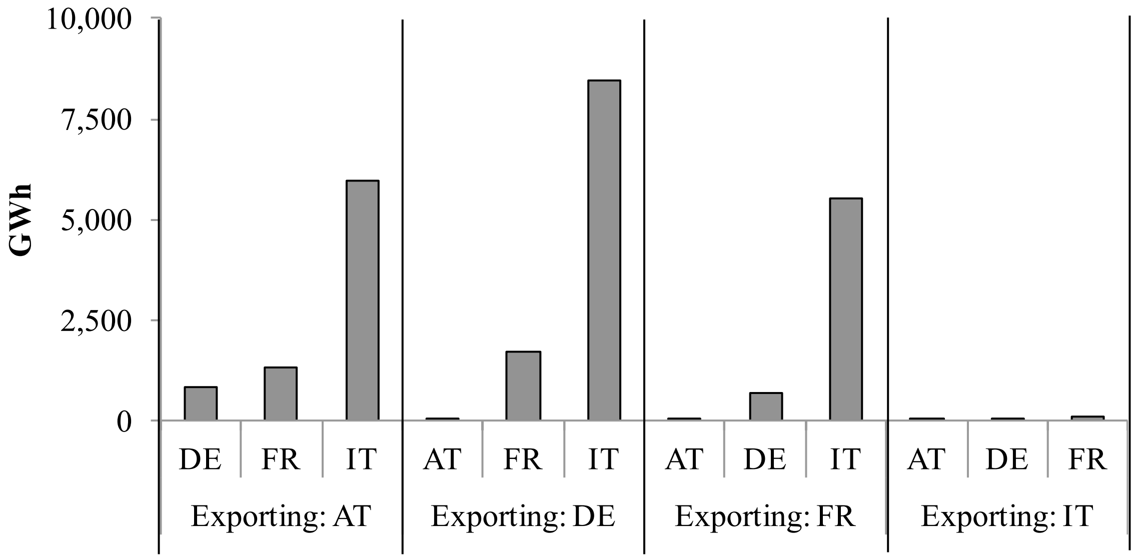

Figure 6-4: Annual Electricity Transit Flows through Switzerland for the Year 2009 (SwissGrid AG 2012b)

It can be seen that Germany exports more than 7.5 TWh of electricity via Switzerland to Italy. This is more than 5% of Italy's total electricity consumption in 2009. France and Austria are also selling electricity to Italy via the Swiss grid. This of course results in strong implications on the electricity consumption GHG emissions for Switzerland if the electricity imported is now directly allocated to Italy. Figure 6-5 visualises the difference between the results of Module I (solid line) and Module I + II.

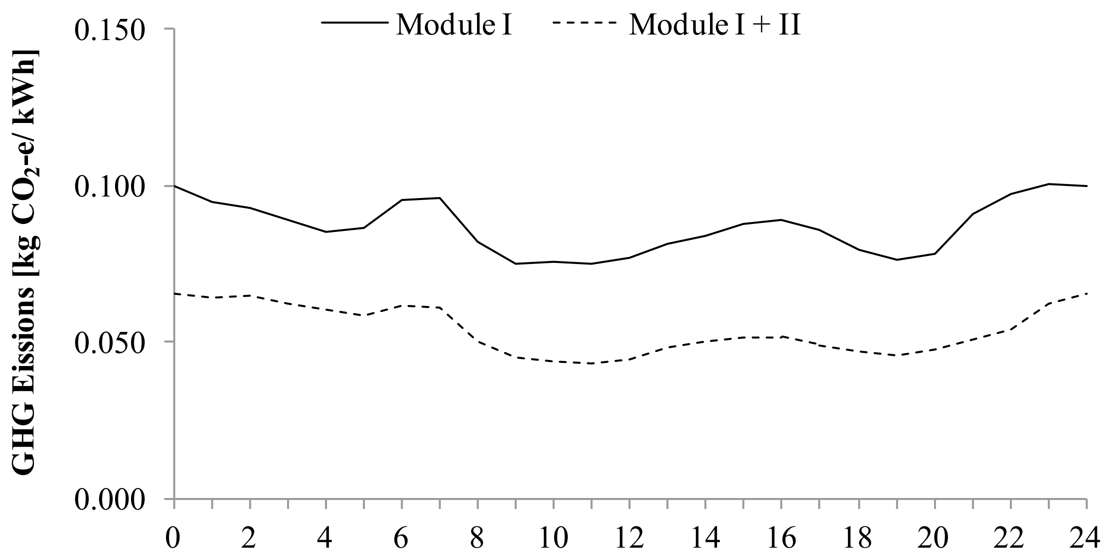

Figure 6-5: The Impact of the Accounting for Transit Electricity Trade on GHG Emissions in Switzerland for the Year 2009

Now, most of the electricity imported from Germany, Austria and France is not accounted for the Swiss consumption mix anymore, but for the Italian electricity consumption mix. As a result, the electricity consumption emissions for Switzerland decrease significantly by almost 50%. It can therefore be concluded that accounting for transit trade can change LCA results significantly. For Italy as well, the consideration of transit trade has a significant impact on electricity consumption emissions as depicted in Figure 6-6.

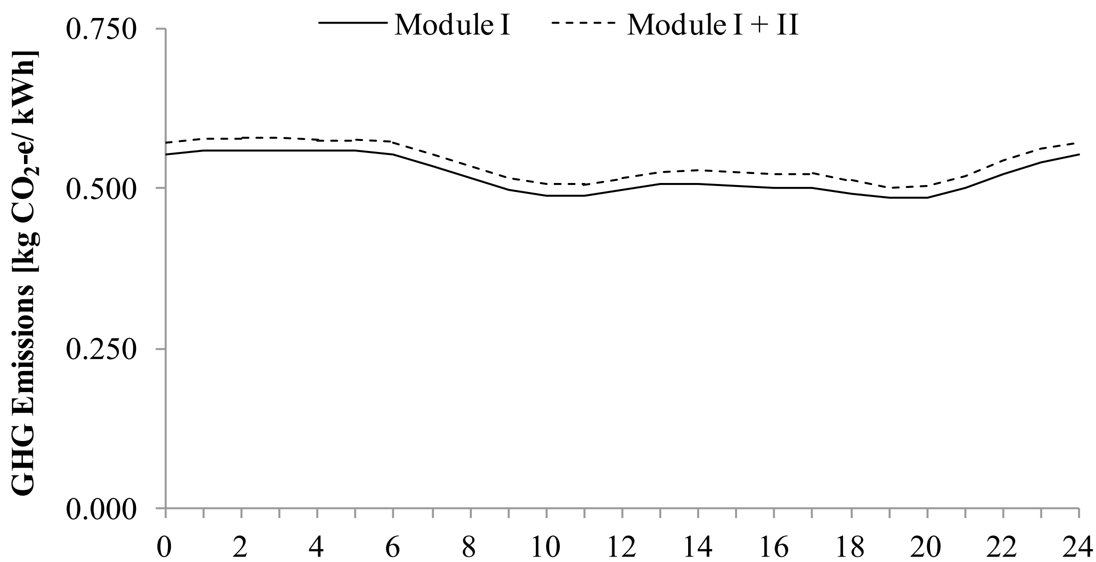

Figure 6-6: The Impact of Accounting for Transit Electricity Trade on GHG Emissions in Italy for the Year 2009

The allocation of German electricity to the Italian electricity consumption mix results in an increase of GHG emissions. Since the electricity consumption emissions for Italy are generally high, the impact is still lower compared to Switzerland. The increase amounts to around 5%.

In the following chapter, the impact of the virtual trade on LCA results is examined.

6.3 Virtual Trade

The amount of virtually traded electricity is increasing, as is the demand for electricity with low GHG emissions. As described in Chapter 4.5, the virtual trade of electricity can have a severe impact on the consumption mix of a country. In this chapter, an example on how to account for virtual electricity trade in the EMM using Module III is presented. As an example, Norway is chosen as it is the dominant trader of electricity certificates in Europe. The annual data used in this example is taken from the Re-Diss Project (European Commission 2012). It is to be noted that this represents an example with the major assumption that all virtual electricity from Norway is sold to Germany since no other data is available. Figure 6-7 shows the impact of the accounting for electricity certificate trade in Norway vs. the results of Module I (solid line).

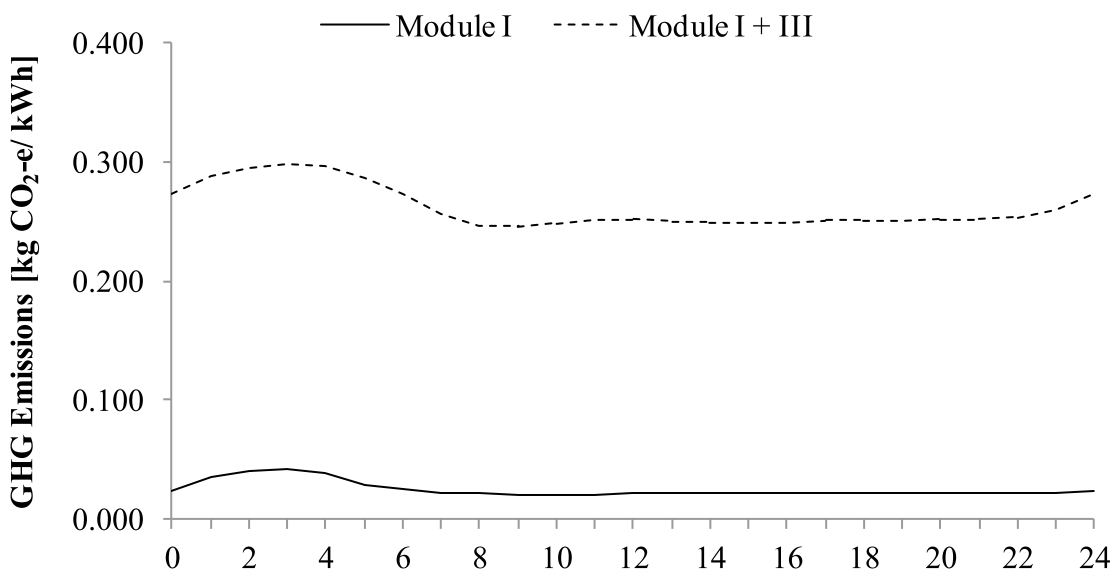

Figure 6-7: The Impact of Accounting for Virtual Electricity Trade on GHG Emissions in Norway for the Year 2009

The electricity consumption emissions for Norway are strongly increasing since many of the attributes of electricity associated with low GHG emissions are sold. As described in Chapter 4.5

the electricity attributes from Germany are imported in return. This results in a tenfold increase of GHG emissions for the electricity consumption of Norway.

It can be summarised that both, the transit trade and the virtual certificate trade can have a severe impact on some countries. The examples of Switzerland and Norway show that the difference between assumptions in current databases and an exact calculation can differ significantly. An inclusion of such data is therefore highly recommended in order to keep the LCA methodology of electricity consumption up to date with the developments in the European electricity market, and in order to produce correct results and avoid the underestimation of GHG emissions from electricity consumption.

7. Conclusions

This extensive study was determined by the research question on: “How can the environmental impact of electricity consumption be quantified with regard to the specific characteristics of the electricity market?” as stated in Chapter 2.7. With the development of a comprehensive model called the Electricity Market Model (EMM) in the study at hand, it is now possible to compute the environmental impact of various forms of trade on the electricity market, and to quantify the influence of storing-in and storing-out of pump storage plants on an hourly basis. The EMM is therefore capable of quantifying the environmental impact of electricity consumption with regard to the specific characteristics of the electricity market.

For the implementation of LCI data of electricity production GaBi data (PE International 2013) is used to estimate the LCI of different power plant types. EWI Köln with their DIMENSION Model (EWI 2011) provides hourly power plant and trade data. The impact of trade is computed based on an economic input output (EIO)-LCA approach using a modified Leontief Matrix as described in Chapter 4.3. This is the first work known to apply EIO-LCA to the electricity market, making it possible to conduct an unbiased assessment of the impacts of electricity trade on electricity consumption emissions. The EMM consists of three modules. Module I quantifies the physical electricity flow between different regions (see Chapter 4.3). Module II corrects the physical electricity flow by quantifying transit trade which cannot be accounted for by Module I (see Chapter 4.4). Module III accounts for electricity certificate trade (see Chapter 4.5). Since the EMM is based on an hourly resolution, the impact of short-time variations in electricity supply, varying electricity demand, trade between countries and the impact of electricity storage systems can be examined sufficiently.

Another important research demand was to examine the relevance of the fluctuating supply/demand and the relevance of the various types of trade. The relevance of the high-resolution approach of the EMM is demonstrated for the eighteen most relevant members of the European Network of Transmission System Operators for Electricity (ENTSO-E) in Chapter 5. Twelve types of power plants in these eighteen European countries are modelled in an hourly resolution. As a result, 8760 individual datasets for each country and each power plant type are generated for the years 2009, 2020 and 2030. This high-resolution approach enables a precise quantification of emissions associated with electricity production and consumption as described in the following chapter.

7.1 The Relevance of Fluctuations in Supply and Demand and a High Time Resolution

A high time resolution approach to electricity production can be important for countries that are supplied by a large share of highly fluctuating renewables such as wind-, solar- and reservoir hydropower plants, as these electricity sources are subject to meteorological variations that cannot be predicted on a long term. At times when renewable resources are underperforming, so-called backup power plants must be switched on in order to ensure that the local electricity demand is met. Another option to meet the demand is the purchase of electricity from neighbouring regions. Both options can lead to variations of GHG emissions. Hence, electricity consumption emissions can deviate significantly from the annual average currently calculated by most LCA methodologies. These deviations can be as high as 100% in the case of Norway as shown in Chapter 5.1.1.1. This is, however the highest possible deviation on an annual basis, which would only occur if an application consumed electricity once a day for one hour each day of the year. In reality, however, it is hard to find applications with a constant electricity consumption pattern like that. Furthermore, if a high-resolution LCI data set is applied for a product or service, all electricity consumers within a region must be assessed using a high time resolution LCI data set in order to maintain consistency. Since this is virtually impossible, the usage of annual consumption emissions factors is the only feasible option for most LCA studies. High time resolution LCI data sets are therefore recommended to be used merely in the course of a sensitivity analysis within a LCA study.

Nevertheless, when it comes to assessing the environmental impact of electricity storage systems, a high time resolution is crucial, since electricity storage systems can switch from consumers to producers within a short period of time. In the context of an annual LCI data set, however, it is negligible as there is only a relatively small share of electricity production from electricity storage systems.

It is worth noting that an annual LCI data set can be computed by using either annual or high-resolution data. High-resolution background data generally increases the precision of annual data sets as shown in Chapter 6.1. High-resolution production data in this context is closely linked to high-resolution trade data.

The impact of physical electricity trade is explained in the following chapter.

7.2 The Relevance of Physical Electricity Trade (Module I)

As shown in Chapter 6.1, it is crucial that an annual LCI data set of electricity consumption is based on hourly physical trade data since errors can be significant if only the annual trade balance is considered. The results show that it is more important to assess trade data on a high-resolution basis than to assess high-resolution electricity production data when computing the LCI of electricity consumption. Physical electricity exchange can have a significant impact on electricity consumption emissions as shown in Chapter 0. Because of the EIO-LCA approach developed in this study, an unbiased assessment of the impacts of electricity trade on electricity consumption emissions is possible.

A central category of physical trade is the transit trade, which plays an important role within electricity markets. Consequently, the following chapter describes the impact of transit trade evaluated in the study at hand.

7.3 The Relevance of Transit Electricity Trade (Module II)

The transit trade case study in Chapter 6.2 demonstrates the impact on the examined countries in 2009. Electricity purchased by Italy in Germany can be transited through Switzerland. By only applying Module I, it is not possible to identify these transit flows. Switzerland imports electricity from Germany, which increases the GHG emissions of the Swiss electricity consumption significantly. On the other hand, Italy imports electricity from Switzerland that reduces the relative GHG emissions for the Italian electricity consumption. With Module II, the transit trade can be quantified and the GHG emissions for the electricity consumption of these countries can be recalculated. This leads to a 30% decrease in GHG emissions for electricity consumption on an annual basis for Switzerland, accounting for the fact that the electricity imported from Germany is directly transited to Italy. As a result, Italy´s GHG emissions for electricity consumption increase by 5%, as compared to the results of Module I. These results indicate a great significance for the consideration of transit trade for countries likely to transit high amounts of electricity. The relevance of transit trade will most certainly increase in the near future and therefore it is highly recommended to include these results in databases if reliable data is available.

7.4 The Relevance of Electricity Certificate Trade (Module III)

The trade of electricity certificates (especially green certificates) without the trade of the corresponding amounts of physical electricity has reached a significant scale in 2009. Important sources for these certificates are hydro power plants in Norway. In the case study in Chapter 6.3, Module III is used to demonstrate the impact of electricity certificate trade on electricity consumption emissions in Norway. In this example, 53 terawatt hours (TWh) of electricity certificates are sold to Germany, whereas only one TWh of physical electricity has been exported in the same period of time. The inclusion of this certificate trade increases the electricity consumption emissions for Norway significantly. In the future, this impact is likely to rise since many companies/countries decide to purchase green electricity certificates in order to decrease their carbon footprint. Therefore, electricity certificate trade must be considered in LCA databases as soon, as there is reliable data available. As described in Chapter 4.5, the EMM provides Module III for the implementation of electricity certificate trade into LCA databases.

The following chapter summarises the implications for the different stakeholders, involved in the environmental assessment of electricity consumption based on the findings of this study.

7.5 Implications of the Findings in this Study

The use of annual consumption emission factors is the only feasible option for most LCA studies. It is therefore recommended that high time resolution LCI data sets are merely used in the course of a sensitivity analysis within a LCA study. It can be concluded, however, that for the set-up of an annual Life Cycle Inventory (LCI) data set of electricity consumption, a higher data resolution generally increases precision. The use of high-resolution trade data is crucial for the compilation of an annual LCI data set of electricity consumption since errors can be significant if only annual trade is considered.

Furthermore, it is crucial to consider transit trade and certificate trade for LCI data sets of electricity consumption in order to avoid an underestimation of emissions associated with electricity consumption. For the consideration of transit trade as well as certificate trade, data availability constitutes a problem since there is no reliable data available yet. In the course of electricity market transparency measures, however, the European Commission is currently working on this problem. As soon as there is reliable data available, the EMM can be updated.

As a result of my study, it can be stated that, with the development of the EMM, it is now possible to provide for a distinct and comprehensive method for assessing the environmental impact of electricity consumption with regard to the specific research questions that could not be satisfactorily answered in the past.

The following chapter describes the limitations of this study as well as an outlook for possible future developments.

7.6 Prospectus

The EMM is capable of accounting for the consumption of electricity on a European scale. Since it is based on a generic approach, it can be extended in terms of dimensions (participating countries) and geographic references (e.g. China, North America, etc.). The time resolution can be adapted to the users' need and most importantly, other impact categories can be implemented into the EMM providing a profound basis for a life cycle sustainability management (FINKBEINER, M. 2011).

Besides the implementation in LCA databases, one of the most promising applications for the EMM can be the environmental optimisation of production processes e.g. at a production site. By determining the most relevant timing (e.g. when GHG emissions are the highest), energy efficiency measures can be implemented most effectively (HESSELBACH, J. et al. 2012) as part of an environmental demand side management (EDSM).

Data availability, however, remains a problem. In the course of this study, the hourly modelling of the European electricity market is done using the DIMENSION Model (EWI 2011) since real time electricity production data is not readily available. It can be assumed that constant efforts to increase transparency with regard to electricity consumption within the European Union leads to increased data availability. At the moment, detailed power plant data can be found at EEX (European Energy Exchange (EEX) 2013) covering 60% of all thermal power plants in Switzerland, Germany and Austria. High-resolution trade data is available for all European countries at ENTSO-E (European Network of Transmission System Operators for Electricity (ENTSO-E) 2013). Hence, for Europe, the EMM can already be implemented in general databases with respect to data availability for the physical exchange of electricity. Since the EMM requires a vast amount of data, it is necessary to sophisticate the EMM further with standard procedures such as the application of automatic updates once new data becomes available. Once a template of hourly power plant data, electricity consumption data and trade data is created, it can be used to load data into the EMM for the assessment of annual LCI data sets for electricity consumption.

The holistic methodology of the EMM can provide for a distinct and comprehensive method of assessing the environmental impact of electricity consumption regarding a dynamic and complex environment such as the electricity market. However, it remains necessary to increase the transparency of the European electricity market to facilitate the provision of detailed production and trade data.

8. References

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Appendix A

Table A- 1: Distribution Losses for the Eighteen Countries Modelled

Country	Total Losses	High Voltage (HV)	Medium Voltage (MV)	Low Voltage (LV)
AT	5.3%	0.4%	0.7%	7.0%
BE	5.0%	0.3%	0.7%	6.6%
CH	6.8%	0.4%	0.9%	9.0%
CZ	7.2%	0.5%	1.0%	9.5%
DE	4.8%	0.3%	0.7%	6.3%
DK	7.0%	0.5%	1.0%	9.2%
ES	4.2%	0.3%	0.6%	5.6%
FI	3.5%	0.2%	0.5%	4.6%
FR	7.7%	0.5%	1.1%	10.2%
GB	7.8%	0.5%	1.1%	10.3%
IE	7.7%	0.5%	1.1%	10.2%
IT	6.6%	0.4%	0.9%	8.7%
LU	1.9%	0.1%	0.3%	2.5%
NL	4.1%	0.3%	0.6%	5.4%
NO	6.6%	0.4%	0.9%	8.7%
PL	10.0%	0.7%	1.4%	13.2%
PT	7.3%	0.5%	1.0%	9.7%
SE	7.4%	0.5%	1.0%	9.8%

Appendix B

Table C- 1: Installed Capacities of Renewable Power Plants in 2020 (FÜRSCH, M. et al 2011) and (Beurskens L. W. M. et al. 2011) [AT – FR]

Installed Capacity [MW] 2020	AT	BE	CH	CZ	DE	DK	ES	FI	FR
Hydropower (Water Reservoir)	4.854		7.583	0.714	0.876		12.576		13.800
Wind Onshore	2.578	-	20	743	45.000	2.621	35.000	-	19.000
Wind Offshore	-	-	-	-	9.000	1.339	3.000	-	6.000
Photovoltaic	322	1.340	70	1.695	51.753	6	8.367	10	4.860
Hydropower (Run-of-River)	5.800	100	6.000	276	4.700	4	1.000	1.500	7.500
Pump Storage									
Biogas	102	427	-	417	3.796	349	400	-	625
Solid Biomass	1.164	2.007	580	-	4.792	2.404	1.187	-	2.382
Liquid Biomass	15	18	-	-	237	26	-	-	-
Geothermal	1	4	-	4	298	-	50	-	80

Table C- 2: Installed Capacities of Renewable Power Plants in 2020 (FÜRSCH, M. et al 2011) and (Beurskens L. W. M. et al. 2011) [GB – SE]

Installed Capacity [MW] 2020	GB	IE	IT	LU	NL	NO	PL	PT	SE
Hydropower (Water Reservoir)		0.221	9.964			23.823		2.343	15.621
Hydropower (Water Reservoir)	-	0.221	9.964			23.823		2.343	15.621
Wind Onshore	14.890	4.094	12.000	131	6.000	4.300	5.600	6.800	4.365
Wind Offshore	12.990	555	680	-	5.178	10.000	500	75	182
Photovoltaic	2.680	-	8.000	113	722	-	3	1.000	8
Hydropower (Run-of-River)	-	-	4.600	15	37	2.800	280	2.622	-
Pump Storage									
Biogas	1.100	62	1.200	29	639	-	980	150	42
Solid Biomass	3.140	91	1.640	30	2.253	100	1.550	367	2.872
Liquid Biomass	-	-	980	-	-	-	-	435	-
Geothermal	-	920	-	-	50	-	75	-	

Table C- 3: Installed Capacities of Renewable Power Plants in 2030 (FÜRSCH, M. et al 2011) and (Beurskens L. W. M. et al. 2011) [AT – FR]

Installed Capacity [MW] 2030	AT	BE	CH	CZ	DE	DK	ES	FI	FR
Hydropower (Water Reservoir)	4.854	-	7.583	0.714	0.876	-	12.576		13.800
Hydropower (Run-of-River)	5.800	100	6.000	276	4.700	4	1.000	1.500	7.500
Wind Onshore	2.992	-	1.860	937	61.000	2.642	40.107	-	25.166
Wind Offshore	-	-	-	-	25.000	1.415	5.163	-	8.500
Photovoltaic	429	1.807	60	1.708	66.034	7	10.315	-	6.892
Pump storage									
Biogas	104	574	-	539	4.342	535	551	-	824
Solid Biomass	1.223	2.703	145	-	5.212	2.698	1.517	-	3.059
Liquid Biomass	15	15	-	-	237	43	-	-	-
Geothermal	1	6	-	4	471	-	88	-	100

Table C- 4: Installed Capacities of Renewable Power Plants in 2030 (FÜRSCH, M. et al 2011) and (Beurskens L. W. M. et al. 2011) [GB – SE]

Installed Capacity [MW] 2030	GB	IE	IT	LU	NL	NO	PL	PT	SE
Hydropower (Water Reservoir)	-	0.221	9,964			23,823		2,343	15,621
Hydropower (Run-of-River)	-	-	4,600	15	37	2,800	280	2,622	-
Wind Onshore	19,318	-	14,401	150	7,300	4,360	7,448	7,152	5,377
Wind Offshore	18,577	-	1,074	-	8,215	22,290	875	113	222
Photovoltaic	3,891	-	10,194	132	1,026	-	4	1,345	10
Pump storage									
Biogas	992	62	1,491	32	896	-	1,543	184	42
Solid Biomass	4,581	103	1,885	43	2,364	100	1,692	367	3,268
Liquid Biomass	-	-	1,215	-	-	-	-	435	-
Geothermal	-	-	977	-	-	50	-	101	-

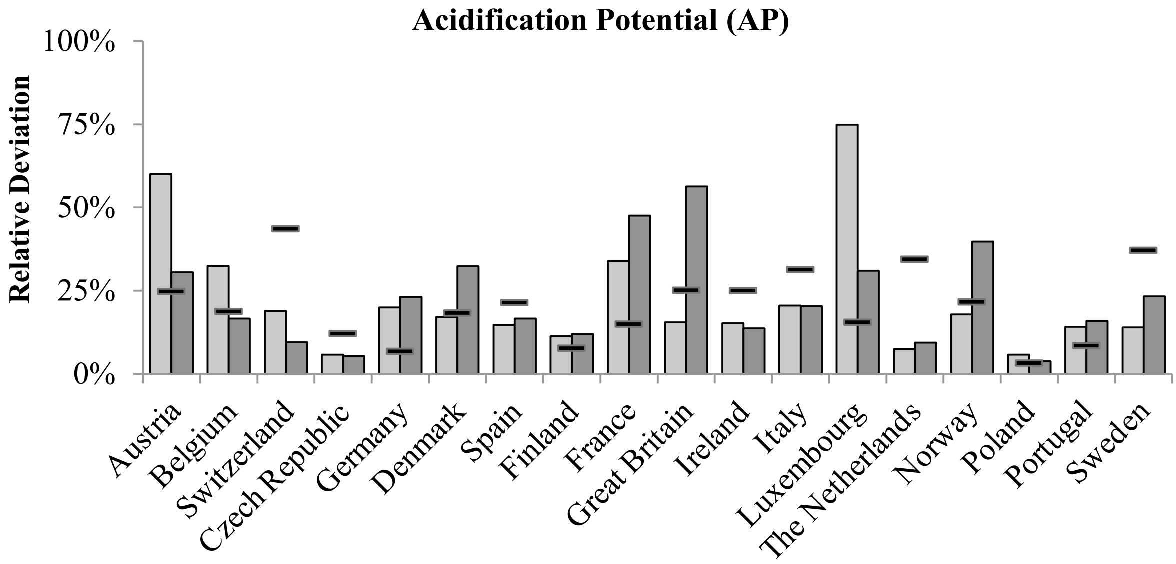

Figure C- 1: **Upper and Lower Deviation of the Average AP of Electricity Production for the Eighteen European Countries for the Years 2009, 2020 and 2030**

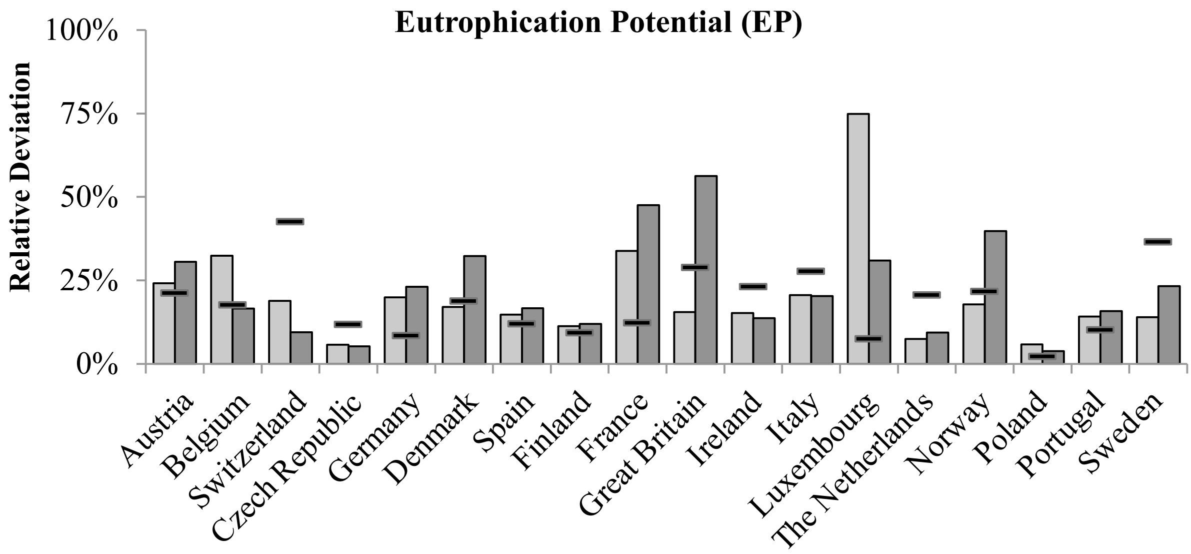

Figure C- 2: **Upper and Lower Deviation of the Average EP of Electricity Production for the Eighteen European Countries for the Years 2009, 2020 and 2030**

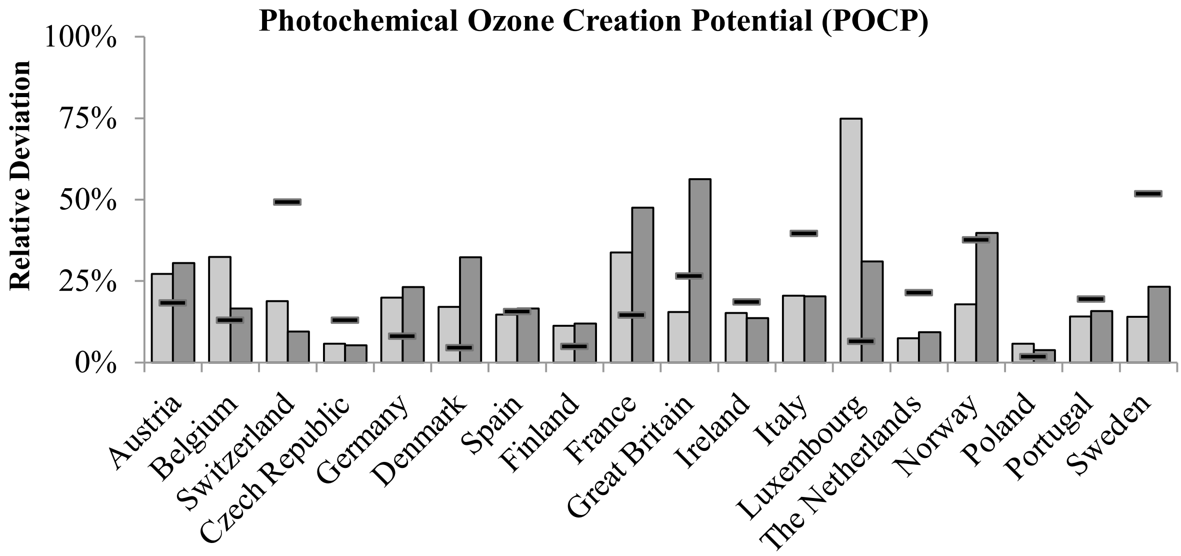

Figure C- 3: Upper and Lower Deviation of the Average POCP of Electricity Production for the Eighteen European Countries for the Years 2009, 2020 and 2030

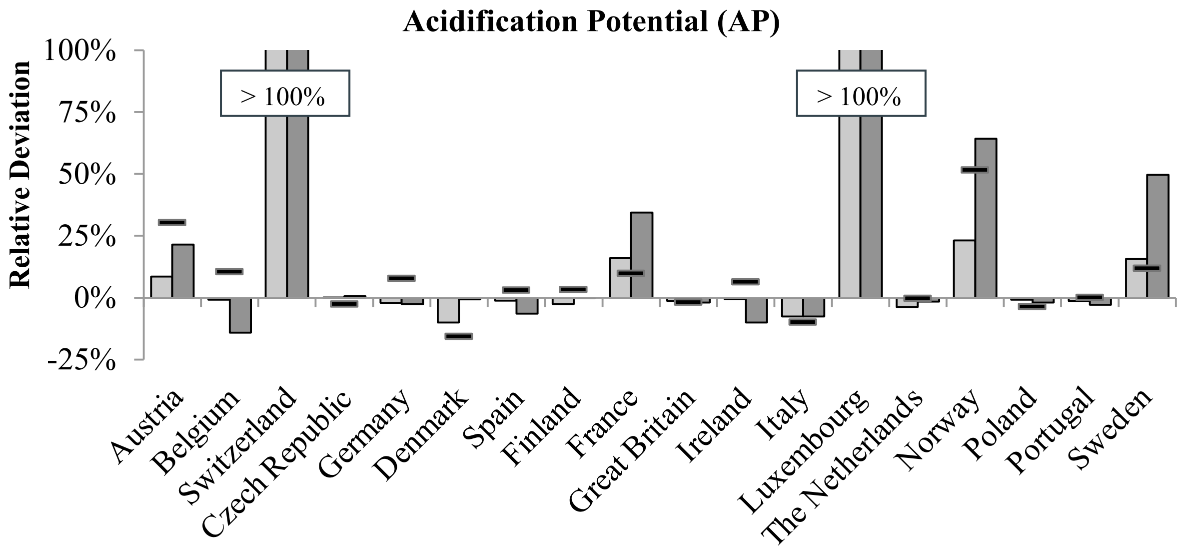

Figure C- 4: Difference between Electricity Production and Electricity Consumption AP for all Eighteen European Countries for the Years 2009, 2020 and 2030

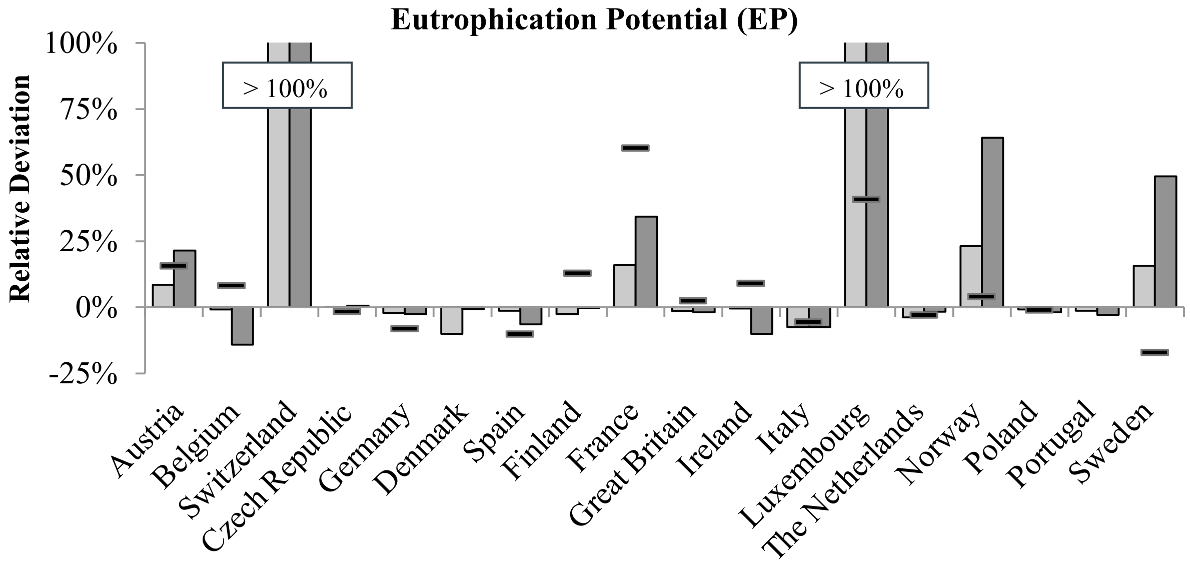

Figure C- 5: Difference between Electricity Production and Electricity Consumption EP for all Eighteen European Countries for the Years 2009, 2020 and 2030

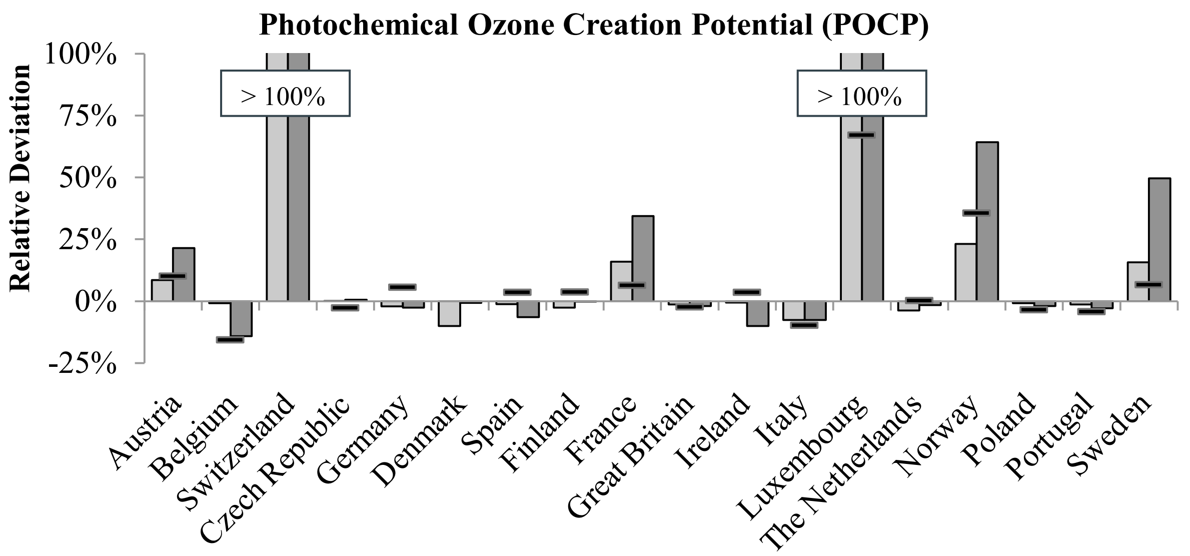

Figure C- 6: Difference between Electricity Production and Electricity Consumption POCP for all Eighteen European Countries for the Years 2009, 2020 and 2030

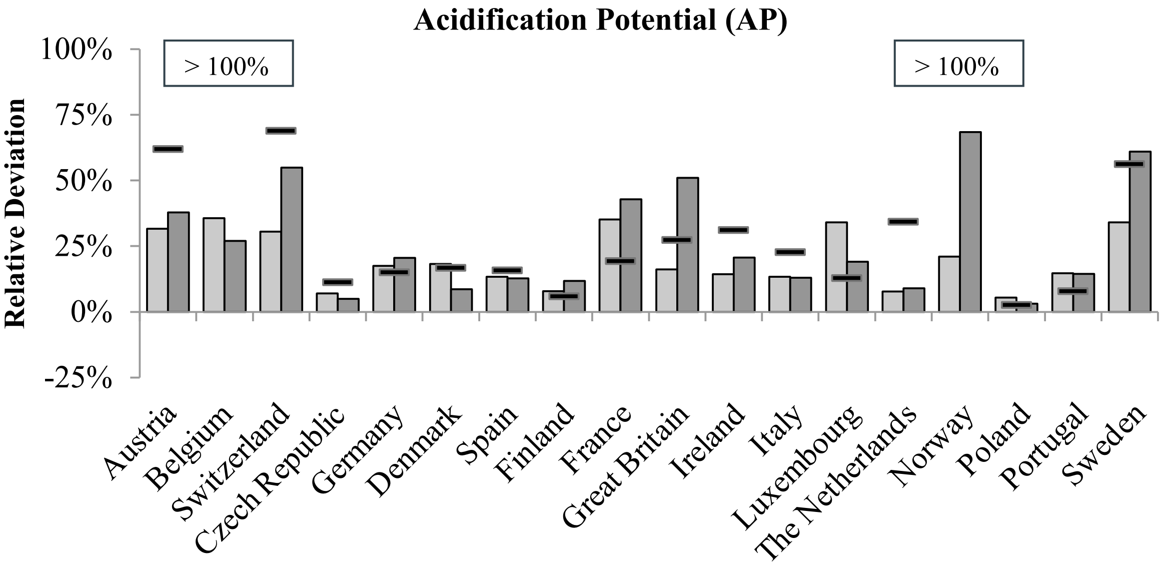

Figure C- 7: **Upper and Lower Deviation of the AP of Electricity Consumption for all Eighteen European Countries for the Years 2009, 2020 and 2030**

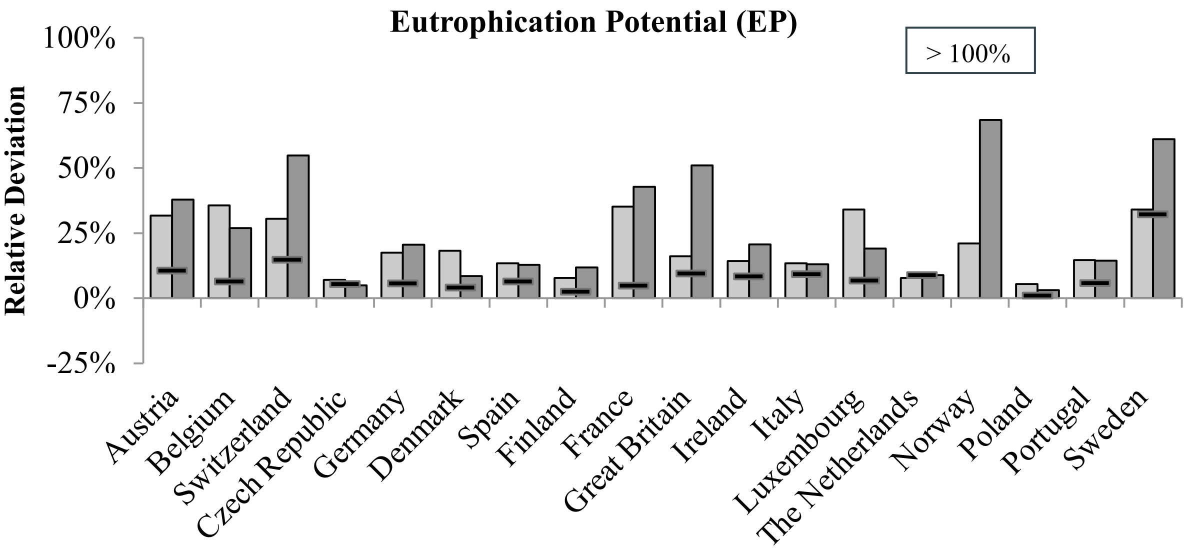

Figure C- 8: **Upper and Lower Deviation of the EP of Electricity Consumption for all Eighteen European Countries for the Years 2009, 2020 and 2030**

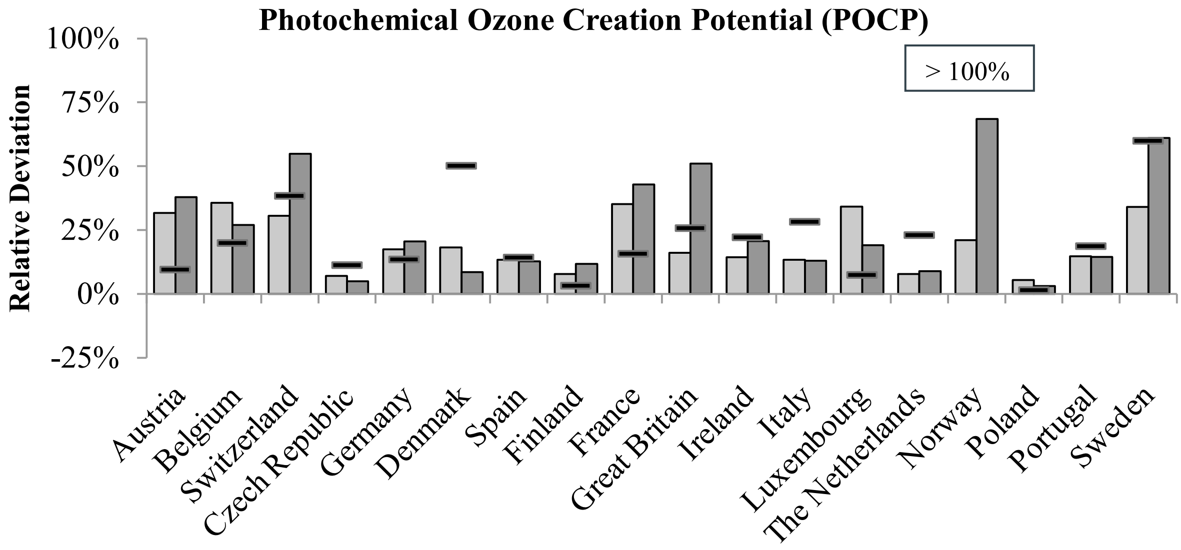

Figure C- 9: Upper and Lower Deviation of the POCP of Electricity Consumption for all Eighteen European Countries for the Years 2009, 2020 and 2030

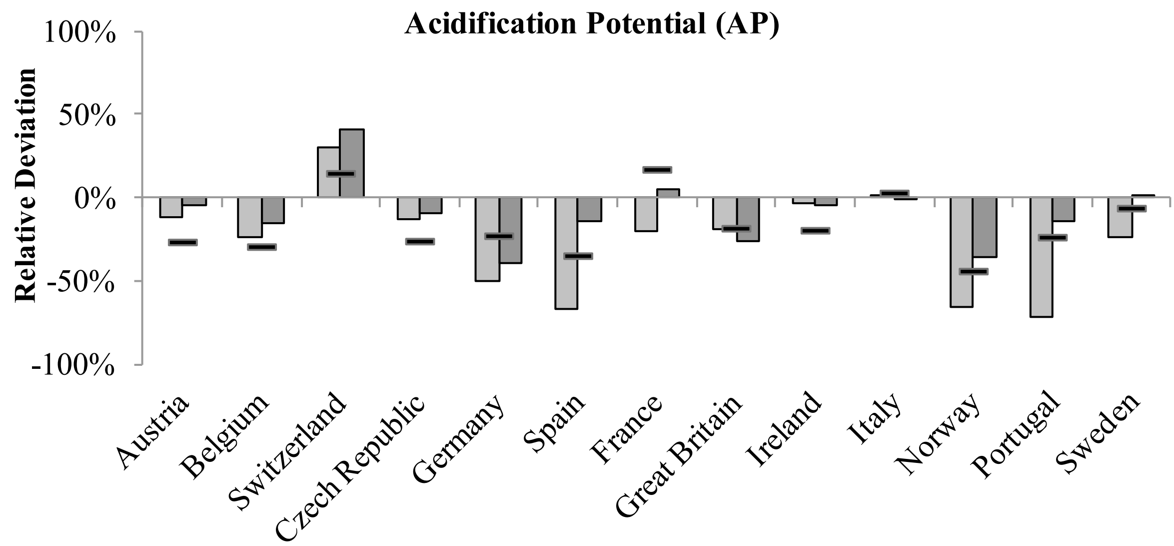

Figure C- 10: Relative Deviation of AP of Electricity Production of Pump Storage Compared to AP Emissions of Electricity Consumption in Countries with Pump Storage for the Years 2009, 2020 and 2030

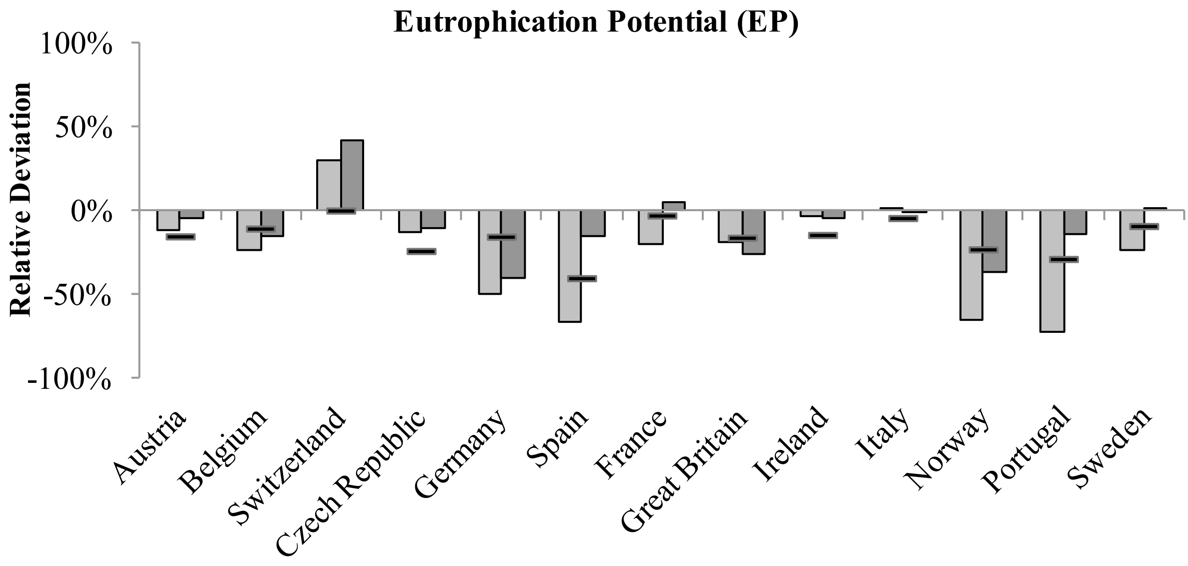

Figure C- 11: **Relative Deviation of EP of Electricity Production of Pump Storage Compared to EP Emissions of Electricity Consumption in Countries with Pump Storage for the Years 2009, 2020 and 2030**

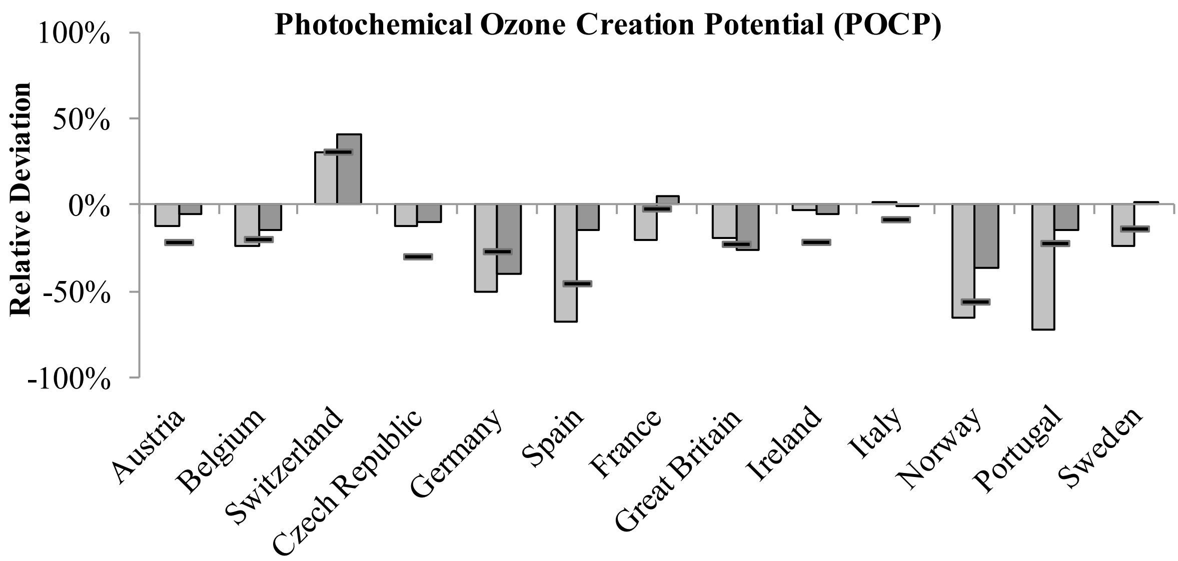

Figure C- 12: **Relative Deviation of POCP of Electricity Production of Pump Storage Compared to POCP Emissions of Electricity Consumption in Countries with Pump Storage for the Years 2009, 2020 and 2030**