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# Supply chains and the role of electricity generation from biomass in the energy systems of Austria and the European Union: an assessment of status, targets, constraints and potentials embedded in a European policy framework

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# Supply chains and the role of electricity generation from biomass in the energy systems of Austria and the European Union: an assessment of status, targets, constraints and potentials embedded in a European policy framework

February 2019

## Parts

# Abstracts

The present work consists of two individual parts:

## Part I

Biomass can serve as replacement or supplement resource in regional energy systems. Significant improvements of conversion technologies and the fact that those processes are, to some extent, regarded as carbon neutral, have made biomass sources considerable feedstocks for electricity and heat generation systems. This work presents a mixed integer linear programming (MILP) approach to model a regional biomass Supply Chain (BSC). Locally available biomass (e.g. wood) from one or several supply locations is used to produce final products such as electricity and heat, after undergoing storage, distribution and pre-processing activities and under consideration of moisture content. The program can serve as decision support system in planning questions, to define locations and capacities of processing sites as well as the necessary distribution systems. The objective is to determine the optimal configuration of a BSC in order to be economically attractive. The model is finally applied to a case study. On top of the MILP model, a graphical user interface (GUI) was created, enabling the user to flexibly adjust the model input data to their needs.

## Part II

In light of global warming, United Nations as well as the European Union have formulated climate and energy strategies with the long-term goal of restraining the increase of Greenhouse Gas Emissions. Consequently, those strategies had a strong impact on the EU's energy systems. Under the Renewable Energy directive, closely interrelated with the Kyoto protocol, a large policy framework to promote Renewable Energy in the EU was established by all Member States to reach national binding targets. This work presents the course of events leading those targets and analyses the differently adopted support mechanisms such as the Feed-In Tariffs. Then, the focus is put on the contribution of biomass (in particular wood) to electricity generation, explaining its role in European energy systems, its potentials and also barriers, supported with statistical figures. Finally, the situation of Renewables and biomass is assessed for the case of Austria. The work concludes that under existing policies, the price of carbon and the strong stake of conventional energy sources (fossil, nuclear), long term projections of biomass contribution are impossible, making its contribution unlikely to be on a large scale.

# Part I

# Optimal design and planning of biomass supply chains

## Abstract

Biomass can serve as replacement or supplement resource in regional energy systems. Significant improvements of conversion technologies and the fact that those processes are, to some extent, regarded as carbon neutral, have made biomass sources considerable feedstocks for electricity and heat generation systems. This work presents a mixed integer linear programming (MILP) approach to model a regional Biomass Supply Chain (BSC). Locally available biomass (e.g. wood) from one or several supply locations is used to produce final products such as electricity and heat, after undergoing storage, distribution and pre-processing activities and under consideration of moisture content. The program can serve as decision support system in planning questions, to define locations and capacities of processing sites as well as the necessary distribution systems. The objective is to determine the optimal configuration of a BSC in order to be economically attractive. The model is finally applied to a case study. On top of the MILP model, a graphical user interface (GUI) was created, enabling the user to flexibly adjust the model input data to their needs.

# Contents

# List of Figures

# List of Tables

# List of abbrevations

**API** Application Programming Interface

**BBEC** Biomass Based Energy Carriers

**BSC** Biomass Supply Chain

**CFD** Computational Fluid Dynamics

**CHP** Combined Heat and Power

**DSS** Decision Support System

**EDSS** Environmental Decision Support System

**GA** Genetic Algorithm

**GHG** Green House Gas

**GIS** Geographic Information System

**GUI** Graphical User Interface

**IDE** Integrated Development Environment

**JRE** Java Runtime Environment

**LP** Linear Programming

**MC** Moisture Content

**MILP** Mixed Integer Linear Programming

**MINLP** Mixed Integer Non-Linear Programming

**MIP** Mixed Integer Programming

**NPV** Net Present Value

**RES** Renewable Energy Sources

**SC** Supply Chain

**ST-N** State-Network

# 1 Introduction

Since governments and communities of states have committed to reducing the carbon footprint of their energy systems, Renewable Energy Sources (RES) have gained importance. Today, wind and solar energy are well evolved technologies for electricity generation. However, their availabilities and fluctuations create gaps, which make biomass resources considerable feedstock for filling those gaps.

Today, two of the most important Biomass Based Energy Carriers (BBEC) are wood products and electricity from biomass. (Ajanovic and Haas, 2014) Due to its extensively large forest area, Austria brings a high potential for wood based energy. According to the Austrian Ministry of Agriforestry, the current usable timber supply has a magnitude of 1,134,781,000 Vfm[1] or 539,020,975,000 tonnes, of which approximately 10% are protected. At present time, forests grow faster than they are harvested, leading to a yearly increase of stock. (BMLFUW, 2015). Figure 1 illustrates the average stock of timber in Vfm/ha per community.

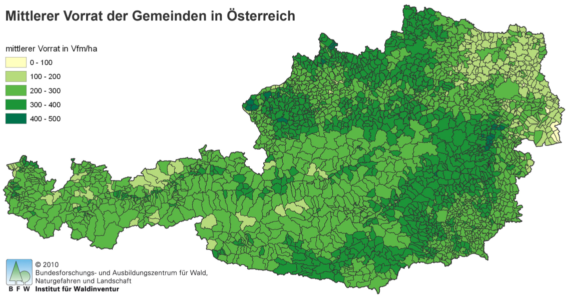

Figure 1: Average stock of timber in Austria (Vfm/ha)

In maximum usage scenarios, potential analysis studies state 34.5 TWh of thermal energy out of forestry products until 2020. (OeIR, 2010) Those high potentials and the fact that biomass combustion is regarded as carbon neutral makes biomass an attractive alternative energy source for various target applications. The extensive usage of BBEC is attractive since it is a local resource and also creates labour.

In contrast to wind turbines and solar panels, biomass processing facilities depend on raw material supply require continuous input of feedstock, which leads to the need for an supply chain. Hence, the BSC with all its investment and estimated future operational cost needs to be taken into account already in the planning phase of a biomass conversion plant in order to decide whether the project is economically viable.

In this paper, a linear programming approach is presented to model a BSC and furthermore optimize it regarding its NPV. The target application is considered to be in a regional extent, assuming a given electricity and/or heat demand. For that reason, a small case study (a political district of Austria) was developed on which the approach is applied.

This work is organised as follows: the first section presents the results of conducted literature reviews, examining existing publications related to the

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[1] A common volume unit for wood; ca. 1 cubic meter

topic. This review is followed by formulating the problem statement and describing the methodology used. The model is then validated with illustrative examples and applied to a case study, which is presented in subsequent sections. The final section draws the major conclusions and discusses results of this work.

# 2 Review of literature

The objective of this section is to review literature related to optimization methods in biomass supply chains, spending more attention on biomass-to-energy applications, especially electricity. Publications from the year 2000 onwards have been reviewed, however most of them were published within the past five years.

When reviewing the literature, an increased interest in the field of BBEC could be observed. The increased interest in biomass feedstock can be explained with the existence of new and more evolved technologies which allow their more efficient use as well as the fact that they are regarded as renewable and carbon-neutral energy sources. (Rentizelas, 2013)

Especially the topic of supply chain analysis, design, modelling and optimization has been found to be a very common topic: A review of supply chain and logistics issues of the bioenergy production was presented by Gold and Seuring (2011), considering published articles between 2000 and 2009.

Mafakheri and Nasiri (2014) provide extensive literature review on supply chain modelling, identifying and analysing states, issues and challenges connected to BSCs. Meyer et al. (2014) review 71 publications (1997-2012) in the same research area but focus mainly on BSC optimization and compare the different models and methods. Both sources however do not limit their reviews on specific final energy carriers, other than Sharma et al. (2013) who concentrates on BSCs for bio-fuel production (e.g. biodiesel) and highlights their different aspects comparable to Mafakheri and Nasiri (2014).

Elia and Floudas (2014) go one step further and also take supply chains of fossil energy sources into account. Finally as a contrast, Wolfsmayr and Rauch (2014) present an extensive review on publications about forest fuel supply chains, published between 1989 and 2011.

## 2.1 Biomass supply chain structures

In biomass supply chains the main operations can be identified as follows:

- Harvest/collection of raw material at supply sites (e.g. forest, field)
- Pre-processing of raw material
- Transport of raw or pre-processed material
- Loading and unloading of raw or pre-processed material
- Storage of raw or pre-processed material
- Final processing of feedstock in energy conversion plants

In a system-wide approach, the BSC activities are usually referred to as *upstream* terminating at the energy exploitation unit (conversion plant), from which the *downstream*, describing the energy products supply chain, originates. (Rentizelas, 2013; Rentizelas et al., 2009)

Naturally, all reviewed publications treat the upstream supply chain, among which a few stop at this point. (Gronalt and Rauch, 2007; Kanzian et al., 2009; Sosa et al., 2015; Windisch et al., 2015). However, the latter one takes demand fluctuations in the downstream supply chain into account.

All remaining sources consider at least one sort of conversion plant in their supply chains. Furthermore, with only a few exceptions (Lin et al., 2015; Vance et al., 2014; Wang et al., 2015) the vast majority additionally respects the downstream supply chain. By saying so, Wang et al. (2012) include the transportation of energy to the end consumer, but in general the downstream supply chain is seen not modelled as such. However, certain aspects are used in their optimization models: a significant number of authors used the respective energy demand as driving parameter in their optimization models. (Akgul et al., 2012; Bazmi et al., 2015; Frombo et al., 2009; Gunnarsson et al., 2004; Palander and Voutilainen, 2013; Rentizelas et al., 2009; Schardinger et al., 2012; Wang et al., 2012)

Another common method was found to be the dealing with uncertainty in the downstream supply chain. This was done by performing sensitivity analysis on certain parameters such as demand or energy prices. (Akhtari et al., 2014; Balaman and Selim, 2014; Cambero et al., 2015; Kanzian et al., 2009; Kazemzadeh and Hu, 2013; Nagel, 2000; Schmidt et al., 2010)

Trink et al. (2010) on the other hand examine the regional economic impacts of bioenergy production for a region in Austria. Freppaz et al. (2004) consider the cost for electricity grid connection of the conversion plants in their optimization model. Finally, Schardinger et al. (2012) present a holistic approach and try to optimize a regional energy system concentrating on biomass feedstock, but under consideration of all energy flows (including other energy sources) as well as land use for food production.

## 2.2 Common types of bioenergy feedstocks

The most common categories of biomass used for bioenergy can be broken down to a broad classification:

- Wood based biomass (forestry)
- Energy crops (plants grown for the purpose of being used as energy source)
- Agricultural residues (animal manure amongst others)
- Waste (municipal and industrial).

All biomass sources show distinctive chemical and physical properties and as a consequence, they all require certain technologies which results in different supply chain characteristics. (Rentizelas, 2013)

An overview about the different types of bioenergy feedstock treated in the examined sources (excluding literature reviews) can be found in Table 1.

The majority of reviewed sources use forestry based feedstock for their models; the larger part considers mainly harvested round-wood, however some authors additionally take forestry residues or by-products of forest product mills into account. (Cambero et al., 2015; Palander and Voutilainen, 2013; Shabani and Sowlati, 2013) The second most common biomass source was found to be energy crops.

A few authors do not bind their model to a specific feedstock and follow a multi-biomass approach, where the model expects certain characteristics of the feedstock as input parameters rather than incorporating fixed values. (Bazmi et al., 2015; Frombo et al., 2009; Rentizelas et al., 2009)

| | W[a] | E[b] | A[c] | M[d] |
|---|---|---|---|---|
| Lin et al. (2015) | | x | | |
| Wang et al. (2015) | | x | | |
| Akhtari et al. (2014) | x | | | |
| Palander and Voutilainen (2013) | x | | | |
| Shabani and Sowlati (2013) | x | x | | |
| Schardinger et al. (2012) | x | x | | |
| Wang et al. (2012) | | x | | |
| Kanzian et al. (2009) | x | | | |
| Cambero et al. (2015) | x | | | |
| Vance et al. (2014) | | | x | |
| Kazemzadeh and Hu (2013) | | x | | |
| Akgul et al. (2012) | | x | | |
| Palander (2011) | x | | | |
| Schmidt et al. (2010) | x | | | |
| Rentizelas et al. (2009) | | | | x |
| Gronalt and Rauch (2007) | x | | | |
| Nagel (2000) | x | x | | |
| Bazmi et al. (2015) | | | | x |
| Windisch et al. (2015) | x | | | |
| Balaman and Selim (2014) | | x | x | |
| Trink et al. (2010) | x | | | |
| Sosa et al. (2015) | x | | | |
| Yilmaz Balaman and Selim (2015) | | x | x | |
| Frombo et al. (2009) | x | | | |
| Freppaz et al. (2004) | x | | | |
| Gunnarsson et al. (2004) | x | | | |

Table 1: Feedstocks in reviewed publications

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[a] Wood based

[b] Energy crops

[c] Agricultural residues/manure

[d] Multiple or undefined

## 2.3 Optimization of biomass supply chains

Determining the optimization potential of biomass supply chains requires analysis of the single activities their unit cost. (Rentizelas et al., 2009) Among reviewed publications, a trend to using linear programming methods for optimization purposes could be observed. A summary is presented below.

### 2.3.1 Supply chains for Biorefineries

Lin et al. (2015) have developed a Mixed Integer Linear Programming (MILP) model using the GAMS software to optimize a biomass-to-bioethanol supply chain, finding its lowest cost setup by analysing relations between preprocessing and transportation costs. The authors compared three different intermediate products of energy crops (pellets, briquettes and ground) in five different supply chain configurations. The results showed that converting biomass to ethanol locally and distribute ethanol is the optimal configuration. They also showed that using pelletizing, the overall cost decreases with longer distances.

A Mixed Integer Programming (MIP) modelling approach was used by Kazemzadeh and Hu (2013) to design a bio-refinery supply chain, determining optimal locations and capacities of bio-refineries for maximizing profits. Additionally the MIPs were combined with stochastic models in order to take uncertainties of fuel market prices, feedstock yield as well as logistic expenses into account.

A hybrid ethanol supply chain was described and optimized by Akgul et al. (2012), using MILP. Compared to other publications, this model is rather static, not allowing to modify parameters such as bio-fuel demand among others. Their goal is minimize the overal Supply Chain (SC) cost by determining the optimal location and biomass cultivation rate (for different, yet fixed types of feedstock).

Wang et al. (2015) followed a different approach, which also aims in optimizing bio-refinery supply chains. In this paper however, the authors use crop growth models to mathematically model the energy crops production. Their objective is to maximize the production and identify suitable land by combining the growth model with a Geographic Information System (GIS). Furthermore, they investigate conversion kinetics, transportation phenomena (using Computational Fluid Dynamics (CFD) modelling) and energy flows within bio-refineries.

### 2.3.2 Wood Supply Chains

Some of the reviewed works were focused only on the upstream BSC:

Kanzian et al. (2009) have developed a GIS-powered Linear Programming (LP) supply chain model, applied on different supply scenarios. Wood chipping is carried out either at terminal stations or at the plant. Similar to Akhtari et al. (2014), transportation costs are identified to be crucial and hence subject of minimization. The paper deals with naturally ocurring seasonal fluctuations in demand, which lead to the need of storage and therefore to higher SC expenses and considers existing as well as new plants.

A different approach was found to be followed by Sosa et al. (2015). They as well treat woody BSC optimization with an LP model and GIS-support, but their model is driven by Moisture Content (MC). The objective function is to minimize the overall supply chain costs. The authors describe an optimized control of the MC of wood chips processed at power plants which influences harvesting volumes, storage times and therefore the supply chain cost.

Moisture content was also subject of the research by Windisch et al. (2015). The authors of this paper do not develop an optimization model based on mathematical programming, but analyse and enhance the feedstock supply process in a forest BSC by predicting the MC using drying models. They show increases in energy output during seasons with high demand, which also lowers the SC cost.

Both Akhtari et al. (2014) and Gunnarsson et al. (2004) formulate LP modelling approaches to optimize woody biomass supply chains for heating systems with the objective of minimizing the overall SC cost:

Gunnarsson et al. (2004) present a model serving as Decision Support System (DSS) for optimal biomass exploitation, locations and quantities. They compare their MILP approach to a heuristic, step-wise LP one, which delivers comparably good results in less than half the time.

The model described in Akhtari et al. (2014) focuses on minimizing the the transportation costs, which are identified as the crucial cost component of the BSC model. They conclude that it is more economic to perform preprocessing (i.e. wood chipping) at supply sources than at terminal storages.

### 2.3.3 Biomass-to-Electricity Supply Chains

In the reviewed literature about BSC optimization, systems with only electricity as final energy carrier have not received much attention (in the review conducted by (Sharma et al., 2013) it is not mentioned at all).

The model developed by Frombo et al. (2009) uses an Mixed Integer Non-Linear Programming (MINLP) model to optimize a wood based BSC. They consider different conversion methods (pyrolysis, gasification and combustion) for biomass-to-electricity conversion in their model, which is combined with a GIS as well as a GUI to serve as a Environmental Decision Support System (EDSS). The objective is to cost minimization under environmental constraints.

An optimization model for a woody biomass based SC serving a power plant was presented by Shabani and Sowlati (2013). In contrast to others, the feedstock supply in this work is purchased rather than harvested. The multi-objective model bases on MILP, assesses an extensive amount of already discussed issues in woody BSCs, and additionally considers ash management. The authors conclude that small power plants show low efficiencies, whereas large plants, showing competitive efficiency values, are connected to logistical problems and therefore higher cost. They identify the highest cost elements to be transportation of (low-dense) material and efficiency.

Yilmaz Balaman and Selim (2015) developed an MILP model for BSCs with anaerobic digestion of energy crops and animal manure as intermediate process, serving a gas-fired power plant. The model has multiple objectives: maximizing the total annual income, minimizing investment cost as well as annual transportation, purchasing and operational cost.

A system-wide (i.e. upstream, conversion and downstream) BSC optimization model was developed by Bazmi et al. (2015). In their MINLP model, the authors determine the distribution and characteristics of different types of processing facilities, in order to minimize the overall generation cost in a palmoil-to-electricity supply chain in Malaysia; all under constraints associated with power demand.

### 2.3.4 Biomass to heat and power

Due to their significantly higher efficiencies, a predominant part of the reviewed works choose multi-generation schemes (Combined Heat and Power (CHP), tri-generation[2]) for their supply chains.

Nagel (2000) developed an MILP model with the objective of minimizing the overall supply chain cost of wood and energy crops based biomass feedstock. It considers several conversion technologies and was designed for three different kinds of operating companies. The spatial resolution is small in order to be applied on one or several regions in Germany. The model also takes disposal cost into account.

In Freppaz et al. (2004) a model has been created which optimizes the exploitation of forest based biomass for conversion into heat and power in a specified area by conserving a sustainable management of the forests. It uses a mathematical programming approach together with a GIS and serves as DSS.

(Schmidt et al., 2010) present their MIP optimization model with the objective of minimizing the total supply chain cost. The chosen conversion technology is wood gasification from domestic forest woods. Green House Gas (GHG) emissions and transportation costs as well as the investment costs of a district heating infrastructure are considered. The authors use GIS and heat demand models to apply the model on the country of Austria and also respect uncertainties with the usage of Monte-Carlo simulations. It is shown that optimal plant locations are predominantly around larger cities.

Another MILP model with multiple objectives was developed by Palander (2011) for modelling optimal energy flows in a CHP fuel procurement supply chain. The author considers not only wood based biomass but also other feedstock (fossil, peat) with the objective of optimized scheduling and delivery of procurement as well as minimal production cost. The model is limited to a single plant and does not allow many adaptations.

This is different in the one developed in Palander and Voutilainen (2013). It is described as an adaptive LP model, targeting multiple objectives by defining constraints in a single objective mathematical model, however, still only a single CHP plant is considered, for simplification reasons. The demand driven model assesses several issues during preprocessing, transportation and storage and the objective function is the overall cost that needs to be minimized.

Wang et al. (2012) have developed an MIP model to optimize the Miscanthus based BSC serving CHP plant(s). The model is demand driven and maximizes the profit by defining optimal locations of facilities and also takes into account different transportation modes as well as carbon emissions. A

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[2] Power, Heat and Cooling

GIS containing the Miscanthus yield for Great Britain (which basically represents the maximum supply) is used as reference data source.

Another CHP-targeted BSC optimization model was published by Balaman and Selim (2014). Their MILP based model is used to design a supply chain which comprises of typical BSC processes, using the biogas from anaerobic digestion of animal manure and energy crops in a gas-fired CHP power station. The objective is to maximize the profit of the entire supply chain.

As a contrast to linear programming approaches, Vance et al. (2014) have designed an efficient, sustainable and cost minimized energy supply chain by using the P-Graph Method (Process-Graph-Methodology). The work considers multiple feedstock classes mainly from renewable nature and is demonstrated on an agricultural region for heat and power generation through agricultural residues.

Finally, Cambero et al. (2015) have developed an MILP optimization model for bioenergy and bio-fuel based on forest residues. The model considers different final energy carriers and hence conversion facilities (CHP plants, bio-refineries) and maximizes the supply chain's NPV over a period of 20 years.

### 2.3.5 Multi-biomass to multiple carriers

The model developed and presented by Rentizelas et al. (2009) aims in optimizing a multi-feedstock BSC in which a tri-generation plant is served. The particularity of this work lies in the flexibility (multiple feedstock types as well as multiple energy carriers) and its holistic approach (considering also the downstream supply chain, i.e. district heating and cooling network). It incorporates constraints of demand as well as social and legislative constraints and works demand driven. The objective is to maximize the NPV of a target project over its lifetime. The authors claim that linear programming is not applicable for this kind of problem which is why their model is developed in MATLAB using a Genetic Algorithm (GA).

# 3 Problem Statement

The goal of this present work is to develop an optimization framework for the design and planning of Biomass Supply Chains (BSCs) in energy systems.

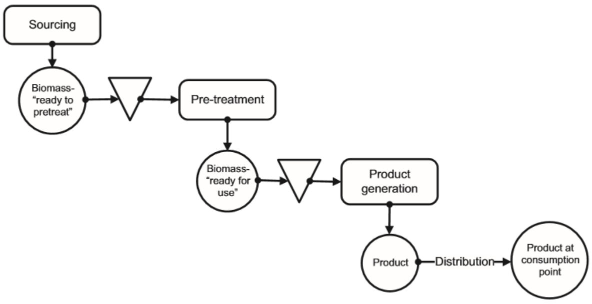

Figure 2: Schematic of a Biomass Supply Chain (BSC)

The BSC comprises of the following operations:

- Harvest/collection of raw biomass feedstock
- Intermediate processing/conversion at different locations and stages of the SC
- Loading and unloading of raw or pre-processed biomass
- Transportation of raw or pre-processed biomass
- Storage of raw or pre-processed biomass
- Conversion of biomass into final energy carrier
- Distribution of final energy carrier

The general schematic is illustrated in Fig. 2.[3] (Pérez-Fortes et al., 2012)

A linear programming approach is considered in order to develop a dynamic optimization model as generic as possible in order to be widely applicable.

The model shall be designed to determine the locations and capacities of processing sites as well as the amounts of material processed and the cost of the supply chain (fixed cost, operational cost, investment cost). The objective is to maximize the NPV of the project (SC including facilities) while partly or fully satisfying demands of power.

On top of the optimization model, a Graphical User Interface (GUI) is designed enabling users to configure it according to their needs and view the results. The results shall serve as Decision Support System (DSS) for the energy industry in strategic and tactical questions regarding investments in BSCs. They are considered to give an estimate about whether or not a project is economically viable within limitations and assumptions and determine this optimal configuration.

## 3.1 Sets

- Materials (raw materials, intermediate materials, final products)

---

[3] Triangles represent transportation activities

- Tasks which produce/consume or distribute materials
- Potential facility locations
- Service suppliers (processing services and raw material supply)
- Equipment technologies
- Planning periods

## 3.2 Parameters

- Mass fractions of tasks producing/consuming materials (recipes for tasks)
- Available amount of raw materials
- Capacity constraints for equipments/locations
- Capacity requirements
- Cost of materials and services
- Demand of final products
- Distances between locations
- Operational cost of processes
- Investment cost for capacity increment
- Final product sales price
- Transportation cost
- Production cost
- Stock handling (storage) cost

## 3.3 Decision variables

- Profit achieved
- Revenue of Sales
- Overall cost
- Net Present Value (NPV) of the BSC project

## 3.4 Constraints

- Maximum amount of raw material to be harvested per period
- Feedstock availability in each (e.g. crop or forest growth)
- Minimum capacity usage
- Capacity limitations regarding expansion

## 3.5 Assumptions

- Demand can be partially satisfied if there is a production shortage and covered with grid imports
- Downstream connection (power grid, heat network) is done at the conversion site and either exists or can be established

- Several supply sites can serve several demand centres (i.e. plants)
- Electricity sales and import prices is constant during a period
- Investments (installation of sites) can be made at the beginning of the planning horizon or at any later time (retro-fitting)
- Final Products can be generated at one or several locations

# 4 Methodology

The problem described in section 3 is formulated as a Mixed Integer Linear Programming (MILP) model adapted from the work presented in (Pérez-Fortes et al., 2012). It is furthermore an adoption of the State-Network (ST-N) formulation developed in (Laínez et al., 2009), which is a well established way of solving this kind of planning problems of Supply Chains (SCs). This flexible network is used to represent the Biomass Supply Chain (BSC), in which any desired production and distribution tasks can be defined within their constraints respectively.

The GAMS[4] software package (version 24.4) was used to implement the mathematical formulation described in this section. The user interface was developed in JAVA Language using Java Development Kit[5] version 1.8 in Eclipse Mars[6] Integrated Development Environment (IDE).

## 4.1 Mathematical Formulation

The ST-N model treats all activities at each node of the SC indistinctly, whether they are result of production or distribution tasks which makes it possible to represent them in a set of only one variable.

In the present model, an activity is denoted by

$$A_{ijff't}$$

which represents the amount resulting from a task $i$ performed in equipment $j$ in location $f$ with destination $f'$. It shall be noted that a production task is performed in one location and hence for production tasks, $f$ is equal to $f'$ (which is obviously not the case for distribution tasks).

Note: $A_{ijff't}$ does not have a fixed unit since it can change as consequence of a task; this will be discussed later, but to give the reader an understanding: activities will mostly be denoted in a mass unit such as kilograms. However, after energy conversion, an input activity in a mass unit can create an output activity in e.g. kilowatt-hours.

This section furthermore describes the mathematical formulation of the model. All symbols (indices, parameters, variables) are listed and described in Appendix B.

### 4.1.1 Mass and energy balance

An important requirement is mass balance, which must be satisfied in every state of the SC. The mass balance requirement is expressed in Eq. (1).

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[4] www.gams.com

[5] www.java.com

[6] www.eclipse.com

$$
\begin{aligned}
S_{mft} - S_{mft-1} = & \\
& \sum_{\substack{i \in I_m \\ i \notin J_w}} \sum_{j \in (J_i \cap J'_f)} \sum_{f' \in J_a} \alpha_{mij} A_{ijf'ft} \\
& - \sum_{\substack{i \in \bar{I}_m \\ i \notin J_w}} \sum_{j \in (J_i \cap J_f)} \sum_{f' \in J_a} \beta_{mij} A_{ijff't} \quad \forall s, f \notin (Mkt \cup Sup), t
\end{aligned} \tag{1}
$$

$S_{mft}$ denotes the stock of material $m$ at location $f$ in time period $t$. Eq. (1) assures that the stock change of material $m$ in location $f$ within two consecutive time periods must be equal to the sum of activities $A_{ijff't}$ of tasks that produce ($i \in I_m$) or consume ($i \in \bar{I}_m$) material $m$ in $f$. Only equipments $j$ that are capable of performing task $i$ ($j \in J_i$) and can be installed at location $f^{(')}$ ($j \in J_{f^{(')}}$) are allowed. $J_a$ is a set of equipments $j$ allowed for material flows between $f$ and $f'$ and is used to assure that no forbidden material flows arise.

The mass fractions of material $s$ produced ($\alpha_{mij}$) and consumed ($\beta_{mij}$) are proportional factors defining the relation between input and output magnitudes of a task $i$ in equipment $j$. It allows to flexibly define different kinds of tasks by modelling all process related parameters with those factors and therefore enforcing the problem's linearity. By using this approach, energy balance is implicitly satisfied through the mass balance.

### 4.1.2 Storage

Storage is regarded as activity in which the unprocessed stock of a material $m$ is taken from the previous (Eq. (3)) and placed in the current period (Eq. (2)).

$$
\begin{aligned}
S_{mf,t} = & \\
& \sum_{i \in I_m} \sum_{\substack{j \in (J_i \cap J_f) \\ j \in J_w}} \alpha_{mij} A_{ijfft} \quad \forall m \notin M_{fin}, f, t
\end{aligned} \tag{2}
$$

$$
\begin{aligned}
S_{mf,t-1} = & \\
& \sum_{i \in \bar{I}_m} \sum_{\substack{j \in (J_i \cap J_f) \\ j \in J_w}} \beta_{mij} A_{ijfft} \quad \forall m \notin M_{fin}, f, t
\end{aligned} \tag{3}
$$

### 4.1.3 Equipment capacity expansion

The following set of equations models the capacity expansion in the facility locations. It shall be noted that capacity expansion can happen at any time period of the planning horizon, not only during the initial design. That is, the formulation is applicable to potential facility locations just as well as to locations with existing capacities.

$\Delta\kappa_{jft}$ represents the increment of capacity of technology $j$ at location $f$ during period $t$: This increment per $t$ has an upper bound which is set by

$\Delta\kappa^{lim}_{jf}$. Eq. (4), using this upper bound, defines the fraction of $\Delta\kappa^{lim}_{jf}$ to be finally expanded. This fraction is represented by $\xi_{jft}$, which is later used in regards to capital investments on fixed assets (Eq. (18), (19)).

$$\Delta\kappa_{jft} \leq \xi_{jft}\Delta\kappa^{lim}_{jf} \quad \forall f, j \in J_f, t \tag{4}$$

$$\xi_{jft} \leq 1 \quad \forall j, f, t \tag{5}$$

$V_{jf}$ (Eq. (6) is a binary variable used to indicate whether or not equipment $j$ is to be expanded at location $f$ at any time during the planning horizon.

$$\sum_t \xi_{jft} \leq \omega V_{jf} \quad \forall f, j \in J_f \cap \notin J_{fin} \tag{6}$$

Finally, Eq. (7) describes the available capacity $\kappa_{jft}$ of equipment technology $j$ at location $f$ during period $t$. The equation takes into account the per-period increment as well as initially available capacity ($\kappa^0_{jf}$)

$$\kappa_{jft} = \Delta\kappa_{jft} + \begin{cases} \kappa^0_{jf} & t \;=\; 0 \\ \kappa_{jf,t-1} & t \;>\; 0 \end{cases} \quad \forall f, j \in J_f \cap \notin J_{fin} \tag{7}$$

### 4.1.4 Equipment capacity utilisation

In order to guarantee equipment capacity being used within its specified bounds, Eq. (8) is introduced. By relating the respective activity to $\theta_{ji}$, which denotes the utilisation factor of task $i$ in equipment $j$, the utilisation of capacity $\kappa_{jft}$ must meet the defined minimum ($\beta_{jf}F_{jft-1}$) and furthermore must not exceed the available capacity.

$$\theta^{min}_{jf}\kappa_{jf,t-1} \leq \sum_{f'}\sum_{i \in J_i} \theta_{ji}A_{ijff't} \leq \kappa_{jf,t-1} \quad \forall f, j \in J_f, t \tag{8}$$

### 4.1.5 Raw material availability

Another constraint of the model is that sourcing is limited to the availability of raw material $m$ at location $f$ in period $t$ ($R_{mft}$). This is established by Eq. (9). The parameter $R^{max}_{mf}$ introduces another constraint, limiting the available amount of collected material to any defined percentage. This is an optional feature available in the model and may be used for sustainability reasons, i.e. to avoid wood thinning.

$$\sum_{f' \notin Mkt}\sum_{i \in \bar{T}_s}\sum_{j \in (J_f \cap J_i)} A_{ijff't} \leq R^{max}_{mf}R_{mft} \quad \forall s \in M_{raw}, f \in Sup, t \tag{9}$$

The available stock of raw material $m$ in location $f$ during period $t$ is calculated in Eqs. (10) and (11). It takes into account the initial available raw material, the removed material from the previous period and additionally considers the growth of raw material during one period $t$. In this approach, the per-period growth of raw material is assumed to be linear for simplicity reasons. Growth of raw materials such as crops or wood is an uncertainty factor. However, the decision maker can define the average annual growth in percent of initially available material.

$$R_{mft} = R^0_{mf} \quad \forall m \in M_{raw}, f \in Sup, t = 0 \tag{10}$$

$$R_{mft} = R_{mf,t-1} - \sum_{f' \notin Mkt} \sum_{i \in \bar{T}_s} \sum_{j \in (J_f \cap J_i)} A_{ijff't-1} + (R^0_{mf} \Delta R_{mf}) \quad \forall m \in M_{raw}, f \in Sup, t > 0 \tag{11}$$

### 4.1.6 Revenue of final product sales

The amount of final product (e.g. electricity) delivered is represented by activity $A_{ijff't}$ with $f'$ being a market location. Eq. (12) calculates the amount of sold final products $m$ to market $f$ ($Sales_{mf'ft}$). The involved task must be a distribution task ($i \in T_d$) producing material $m$ ($i \in I_m$) with $m$ being a final product. The revenue per period $t$ and the overall revenue are then subsequently calculated in Eq. (13) and (13).

$$Sales_{mf'ft} = \sum_{\substack{i \in I_m \\ i \in T_d}} \sum_{\substack{j \in J_f \\ j \in J_i}} A_{ijf'ft} \quad \forall m \in M_{fin}, f \in Mkt, f' \notin Mkt, t \tag{12}$$

$$Rev_t = \sum_{m \in M_{fin}} \sum_{f \in Mkt} \sum_{f' \notin (Mkt \cup Sup)} \rho^{sale}_{mf} Sales_{mf'ft} \quad \forall t \tag{13}$$

$$Rev^{tot} = \sum_t Rev_t \quad \forall t \tag{14}$$

### 4.1.7 Demand satisfaction and imports

The present model allows the demand to be satisfied by the supply chain equipment only partially, which can be the case when (a) shortages of supply arise (b) any capacity constraints limit production or transportation activities (c) it is favourable for the optimization objective. In case supply chain activities do not deliver sufficient final products to satisfy the demand, the difference is imported from an external source (e.g. the power grid). This constraint is formulated in Eq. (15) for all final products $m$ sold to markets $f$. The variable $Imp_{mft}$ takes the difference between sold final product and target demand.

$$\sum_{f' \notin Mkt} Sales_{mf'ft} + Imp_{mft} = Dem_{sft} \quad \forall m \in M_{fin}, f \in Mkt, t \tag{15}$$

As a consequence of acquired imports, the related costs $\Psi^{imp}_t$ per period $t$ are derived in (16) by multiplying them with the unitary price $\rho^{imp}_{mf}$.

$$\Psi^{imp}_t = \sum_{m \in M_{fin}} \sum_f \rho^{imp}_{mf} Imp_{mft} \quad \forall m \in M_{fin}, f \in Mkt, t \tag{16}$$

Eq. (17) sets the binary variable $Z_{f'f}$ to 1 whenever a flow of final material from location $f'$ to $f$ exists. Here, $\omega$ is a sufficiently large integer value. $Z_{f'ft}$ is later used in Eq. (19) to calculate investment expenses for setting up the final product distribution system (e.g. power grid).

$$\sum_{\substack{j\in J_{fin}\\ j\in J'_f}} A_{ijf'ft} \leq \omega Z_{f'f} \quad \forall m\in M_{fin}, i\in (I_m \cap T_d), f\in Mkt, f'\notin Mkt, t \tag{17}$$

### 4.1.8 Capital Investment

Previously presented equations have evaluated the necessary installation and/or expansion of equipment capacities (cf. section 4.1.3). The following equations (19) and (18) determine the capital investments on fixed assets, i.e. the cost of installing and expanding equipment per time period $t$.

$$\Psi_t^{Asset} = \sum_f \sum_{j\notin J_{fin}} \Psi_{jf}\xi_{jft} \quad \forall t > 0 \tag{18}$$

The installation of a final product distribution network such is taken into account in the first planning period: $\Psi_m^{Dist}$ represents the investment cost per unit length for a final product $m$ distribution network, which is multiplied with the respective distance $\lambda_{ff'}$ between locations interconnected locations ($Z_{ff'}$).

$$\begin{aligned}\Psi_t^{Asset} =& \sum_f \sum_{j\notin J_{fin}} \Psi_{jf}\xi_{jft} + \\ & \sum_{m\in M_{fin}} \sum_{\substack{j\in J_a\\ j\in J_{fin}}} \sum_{f\notin Mkt} \sum_{f'\in Mkt} \Psi_m^{Dist}\lambda_{ff'}Z_{ff'} \quad \forall t = 0\end{aligned} \tag{19}$$

### 4.1.9 Fixed and variable cost

Eq. (20) calculates the fixed cost $\Phi_t^{fix}$ of the SC operations in every period $t$. Those fixed costs are derived from the installed capacity $\kappa_{jft}$, which is multiplied with the unitary fixed costs of equipment $j$ in facility $f$ per period $t$. This factor is represented by $\chi_{jf}^J$.

$$\Phi_t^{fix} = \sum_{f\notin Mkt} \sum_{j\in J_f} \chi_{jf}^J \kappa_{jft} \quad \forall t \tag{20}$$

The calculation of variable costs is established by the following set of equations. In this model, all variable costs are expressed in terms purchasing costs made to respective suppliers. Introducing a set of suppliers $s$ makes sense in a way that there might be multiple suppliers offering similar services but for different prices. Furthermore, supply service providers do not necessarily need to provide their services in every potential location. Hence, this approach gives more flexibility to the model.

As shown in Eq. (21), they comprise of costs for raw material acquisition, production services as well as transportation and distribution services. The overall purchasing expenses to supplier $s$ (i.e. the variable cost) during period $t$ is expressed by $Purch_{st}$. The three cost components are furthermore calculated in Eq. (22)-(24).

$$Purch_{st} = Purch_{st}^{Raw} + Purch_{st}^{Tr} + Purch_{st}^{Pr} \quad \forall e, t \tag{21}$$

Eq. (22) sums up all raw material collection related activites, multiplied with $\chi_{smt}^{Raw}$ (which represents the cost of one unit material $m$ from supplier $s$ during period $t$).

$$Purch_{st}^{Raw} = \sum_{m \in M_{raw}} \sum_{f \in F_s} \sum_{f'} \sum_{\substack{i \in \bar{I}_m \\ i \in T_d}} \sum_{j \in J_i} \chi_{smt}^{Raw} A_{ijff't} \quad \forall s \in S_{raw}, t \tag{22}$$

In a similar way, Eq. (23) determines the purchasing costs for all transportation activities. Here, $\chi_{smt}^{Tr}$ is the cost for transportation over a unit distanceat supplier $s$ during $t$. This is multiplied with the distance between locations ($\lambda_{ff'}$) and furthermore with the turtuosity factor $\tau$. The latter one can be set to 1 in case the distances are exact values.

$$Purch_{st}^{Tr} = \sum_{i \in T_d} \sum_{\substack{j \in J_i \\ j \in J_s}} \sum_{f} \sum_{f'} \chi_{smt}^{Tr} \tau \lambda_{ff'} A_{ijff't} \quad \forall s \in S_{tr}, t \tag{23}$$

Eventually, Eq. (24) considers the cost of production activities. On the one hand, all production related activities $A_{ijfft}$ are multiplied with $chi_{smt}^{Pr}$, which measures the unitary production cost related to task $i$ using equipment $j$ in location $f$, provided by supplier $s$ during period $t$. On the other hand, the equation also considers storage activities, since they are provided by production services suppliers. This is established by multiplying the stock $S_{mft}$ with the unitary cost $\chi_{smt}^{Stor}$ of handling material $m$ during period $t$ at supplier $s$.

$$Purch_{st}^{Pr} = \sum_{f} \sum_{i \notin T_d} \sum_{\substack{j \in J_i \\ j \in J_f}} A_{ijfft} \chi_{smt}^{Pr} + \sum_{m} \sum_{\substack{f \notin Sup \\ f \in Mkt}} S_{sft} \chi_{smt}^{Stor} \quad \forall e \in S_{pr}, t \tag{24}$$

### 4.1.10 Overall Cost

The total cost per period as well as the overall cost of the supply chain are calculated in the following equations.

$$\Phi_t = \Phi_t^{fix} + \sum_{s} Purch_{st} \quad \forall t \tag{25}$$

$$\Phi^{tot} = \sum_{t} \Phi_t \tag{26}$$

### 4.1.11 Revenue and NPV

The achieved profit in each period $t$ is expressed by the difference of revenue and cost (Eq. (27)). The overall profit is then calculated in Eq. (28).

$$Profit_t = Rev_t - \left( \Phi_t^{fix} + \sum_e Purch_{st} + \Psi^{Imp} \right) \quad \forall t \tag{27}$$

$$Profit^{tot} = \sum_t Profit_t \tag{28}$$

The Net Present Value (NPV) is finally derived in Eq. (29) by summing up the present discounted values of each period $t$ using the defined discount rate $r$.

$$NPV = \sum_t \left( \frac{Profit_t - \Psi_t^{Asset}}{(1+r)^t} \right) \tag{29}$$

### 4.1.12 Other decision variables

This section shows the calculation of other decision variables which are used for the results presentation.

Eq. (30) and (31) derive the amount of collected raw material per period $t$ and the over all periods.

$$Coll_t = \sum_{m \in M_{raw}} \sum_{f \in Sup} \sum_{f'} \sum_{\substack{i \in \bar{I}_m \\ i \in T_d}} \sum_{\substack{j \in J_i \\ j \in J_f \\ j \in J_a}} A_{ijff't} \quad \forall t \tag{30}$$

$$Coll^{tot} = \sum_t Coll_t \tag{31}$$

The final equations Eq. (32) and (33) calculated the sum of all imported final products $m$ in all locations $f$ as well as distributed final product per period $t$.

$$Imported_t = \sum_{m \in M_{fin}} \sum_f Imp_{mft} \tag{32}$$

$$Distributed_t = \sum_{m \in M_{fin}} \sum_f \sum_{f' \in Mkt} \sum_{\substack{i \in \bar{I}_m \\ i \in T_d}} \sum_{\substack{j \in J_i \\ j \in J_f \\ j \in J_{fin}}} A_{ijff't} \quad \forall t \tag{33}$$

## 4.2 GUI

The GUI created for using this model was developed using the Java programming language. This section briefly describes the main concepts. The GAMS software package provides an Application Programming Interface (API) for being used with Java. The features of this API were used for the purposes of the present work.

Illustrations of the application are shown in Appendix A. The user interface is simple to use and provided with a short descriptive manual.

### 4.2.1 Architecture

The application build path includes Java Runtime Environment (JRE) System libraries and imports the GAMS Java API as referenced library.

The program source comprises of the packages and classes listed in Table 2.

| Package name | Members |
|---|---|
| *com.leclu.gams.gui* | class *ExcelAdapter* |
| | class *Gui* |
| | class *GuiTabbedPane* extends *JTabbedPane* |
| | class *GuiTab* |
| | class *MessageConsole* |
| *com.leclu.gams.gui.tabs* | class *AbstractTab* extends *GuiTab* |
| | class *TabLaunch* extends *AbstractTab* |
| | class *TabParameters* extends *AbstractTab* |
| | class *TabSets* extends *AbstractTab* |
| | class *TabSubsets* extends *AbstractTab* |
| | enum *CreateTabsInit* |
| | enum *CreateTubsRuntime* |
| | interface *MyTabInterface* |
| *com.leclu.gams.model* | class *BSCModelHeader* |
| | class *BSCModelInterface* |
| | class *BSCModelResults* |
| | class *BSCDataIllustrative*1 |

Table 2: Application package overview

The following Tables give an overview about the application components and their functions: Table 3 describes packages, Table 4 package members.

| Package name | Description |
|---|---|
| com.leclu.gams.gui | Contains classes that establish the main framework for the GUI elements as well as the application entry point |
| com.leclu.gams.gui.tabs | Contains classes for the structural definition of tabs to be shown in the user interface |
| com.leclu.gams.model | Contains classes building the interface between GUI and GAMS, including methods to fetch user input data and control the model execution |

Table 3: Application packages description

### 4.2.2 GAMS Java API

The GAMS Java API enables a Java application to interact directly with the installed GAMS distribution. It provides classes and methods to:

- create and configure a *GAMS workspace*, which builds the environment for the execution

- setup a *GAMS database* which contains all model specific symbols and data values
- define a *GAMS job* based on a model and a database
- run this job and read back the results

Hence, the GUI application is responsible for collecting the appropriate data, format them accordingly and deliver them to the *GAMS database*. After reading back the results it furthermore establishes the result presentation.

In the working directory, the API will create all known files that come along with a GAMS model: the .GMS file itself (it is coded into the program), the .LST file (compilation and solution reports) as well as .GDX files for input (created by the API) and output (created by GAMS) data. Using *gdx2xls* (provided with the GAMS distribution), the results are converted to .XLS format (Microsoft Excel) and can be analyzed.

| Member name | Description |
|---|---|
| class *ExcelAdapter* | Enabling copy paste from and to Excel |
| class *Gui* | The application entry point; builds the user interface and invokes the tab environment |
| class *GuiTabbedPane*<br>extends *JTabbedPane* | Provides the tab environment and triggers tab creation |
| class *GuiTab* | The base class for a tab |
| class *MessageConsole* | Building the console window |
| class *AbstractTab*<br>extends *GuiTab* | Inherits the base tab class adding methods; acts as a parent class for all subsequent tabs |
| class *TabLaunch*<br>extends *AbstractTab* | Builds the first tab containing launch configuration and buttons to control execution |
| class *TabParameters*<br>extends *AbstractTab* | An abstract class for model parameter tabs; each instance builds a tab for input of a specific model parameter |
| class *TabSets*<br>extends *AbstractTab* | Builds the input mask for entering set data |
| class *TabSubsets*<br>extends *AbstractTab* | Builds the input mask for entering subset data |
| enum *CreateTabsInit* | A parameter list responsible for building initially visible tabs (i.e. on application launch) |
| enum *CreateTubsRuntime* | A parameter list responsible for building tabs during runtime (i.e. triggered by user) |
| interface *MyTabInterface* | An interface providing methods to exchange data between packages and classes |
| class *BSCModelHeader* | A class containing the model source code (GAMS) as well as its representation in Java (i.e. sets, subsets, parameters, variables and their description) |
| class *BSCModelInterface* | The class that creates and runs the GAMS job |
| class *BSCModelResults* | The class responsible for analysing and displaying results |
| class *BSCDataIllustrative*1 | Contains the pre-loaded data of illustrative example 1 |

Table 4: Application package members description

# 5 Model application: Illustrative examples

This section describes the application of an two illustrative examples on the developed model. The purpose of this step is to demonstrate its main capabilities and to verify the mathematical formulation. All examples were solved and optimized using the GAMS Software with CPLEX 11.1.1, running on an 2.30GHz AMD Phenom 9650 Quad-Core Processor.

## 5.1 Illustrative Example 1

The first is the most simple example of a SC: it builds on a network, where every node of the network is represented only once. For the Biomass Supply Chain (BSC) this means: there is a single raw material supply location as well as a only one demand location (market). Furthermore, every activity is hosted at a unique facility. The considered raw material is forest wood, electricity is the final product.

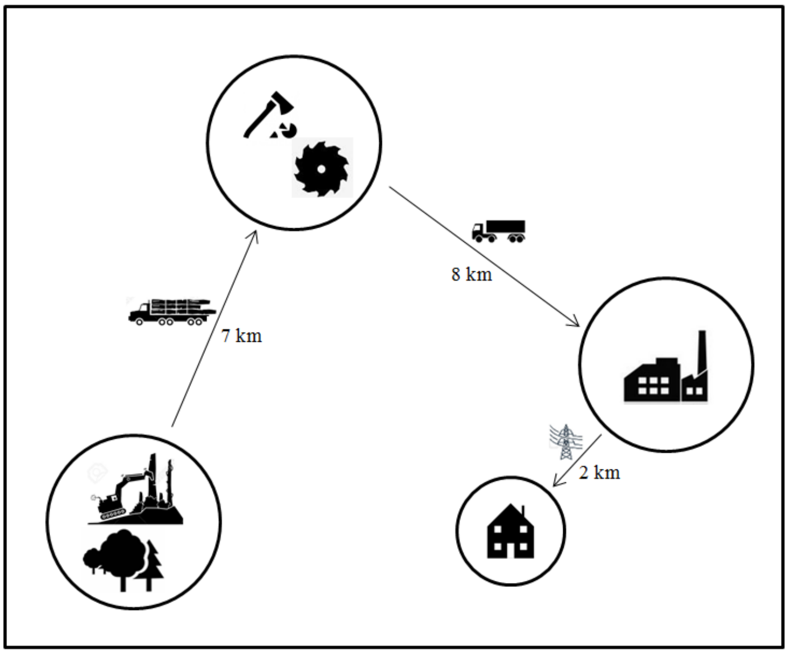


Figure 3: First illustrative example: forest wood biomass supply chain

### 5.1.1 BSC Configuration

The configuration of the example BSC is depicted in Fig. 3. It comprises of the following (intuitively named) elements:

- Facility locations (4): *locRaw, locChipper, locPlant, locMarket*
- Tasks (6): *harvesting, transportation, chipping, combustion, distribution, storing*
- Equipment technologies (6): *harvester, truck, plant, chipper, grid, storage*
- Materials (3): *wood, woodchips, electricity*

| | NPV | Revenue | Cost | Profit |
|---|---|---|---|---|
| | M€ | M€ | M€ | M€ |
| $MAX_{NPV}$ | 1.050 | 19.152 | 9.588 | 2.292 |
| $MIN_{Cost}$ | -17.843 | 6.300 | 4.160 | -2.441 |
| $MAX_{Revenue}$ | -68.829 | 19.152 | 19.456 | -7.576 |
| $MAX_{Profit}$ | -1.213 | 19.152 | 9.363 | 2.517 |

Table 5: Illustrative Example 1 - Results comparison (Economics)

After being collected from the supply side (forest), the raw material (wood) is shipped to the chipping location for being transformed into wood-chips. The wood-chips are transported (using trucks) to the combustion plant, in which they are converted to electricity. All tasks are matched to their equipment and location (e.g. task *harvesting* is performed by technology *harvester* in location *locRaw*). The harvesting task is regarded as distribution task, delivering material from the supply to the chipping site. In the cost calculations, this is taken into account by both considering raw material cost and transportation cost.

### 5.1.2 Input data and expectations

The data chosen for this model is not based on a case study.

Material units are generally regarded in tonnes (in fact, the user can decide which units to use). All material conversions and distribution activities are assumed to be ideal (e.g. 1 tonne of wood results in 1 tonne of woodchips). The final step, *combustion*, is an exception: here, the units are converted from tonnes to kilowatt-hours, using an ideal ratio of 3,500. For the economic assessment, a planning horizon of five years with a discount rate of 15% was chosen. The sales price of electricity is €0.12/kWh, in contrast, the market price for imported electricity is €0.18/kWh.

By applying this example it is expected that all equipment technologies are installed at their predestinated sites, since they are unique and, in order to deliver a final product, all intermediate steps performed by those are required. The simplicity of structure and data is intended: it assures that one can follow the network flow and understand the methodology.

The illustrative example was solved four times with different objectives:

1. To maximize the NPV
2. To minimize the overall SC cost
3. To maximize the overall revenue
4. To maximize the overall profit

### 5.1.3 Results and discussion

In all of the four scenarios, all types of equipments are installed (naturally, as expected). Tables 5 and 6 compare result values of the four decision variables. Tables 7, 8, 9 and 10 contain more detailed results of the NPV maximization scenario.

|  | Collected wood | Prod. power | Imported power |
|---|---|---|---|
|  | t | GWh | GWh |
| $MAX_{NPV}$ | 45,600 | 159.6 | 40.4 |
| $MIN_{Cost}$ | 20,000 | 52.5 | 147.5 |
| $MAX_{Revenue}$ | 45,600 | 159.6 | 40.4 |
| $MAX_{Profit}$ | 45,600 | 159.6 | 40.4 |

Table 6: Illustrative Example 1 - Results comparison (Material)

| Equipment | Location | Installed capacity (h) |
|---|---|---|
| harvester | locRaw | 10,000 |
| chipper | locChipper | 14,286 |
| truck | locChipper | 14,286 |
| plant | locPlant | 14,286 |

Table 7: Illustrative Example 1 - installed capacity

| Period | Inv. cost (€) | Fix cost (€) |
|---|---|---|
| t0 | 1,596,428.57 | 142,857.16 |
| t1 |  | 142,857.16 |
| t2 |  | 142,857.16 |
| t3 |  | 142,857.16 |
| t4 |  | 142,857.16 |

Table 8: Illustrative Example 1 - fixed and investment cost

| Period | Raw material (€) | Production (€) | Transportation (€) |
|---|---|---|---|
| t0 | 0 | 0 | 0 |
| t1 | 1,428,571.43 | 1,428,571.44 | 150,000 |
| t2 | 1,000,000 | 1,428,571.44 | 150,000 |
| t3 | 692,000 | 988,571.44 | 103,800 |
| t4 | 714,285.71 | 714,285.73 | 75,000 |

Table 9: Illustrative Example 1 - variable cost

| Period | Revenue (€) | Cost (€) | Profit (€) |
|---|---|---|---|
| t0 | 0 | 142,857 | -142,857 |
| t1 | 6,000,000 | 3,3150,000 | 2,849,999 |
| t2 | 6,000,000 | 2,721,428 | 3,278,571 |
| t3 | 4,152,000 | 1,927,228 | -547,228 |
| t4 | 3,000,000 | 1,646,428 | -3,146,428 |

Table 10: Illustrative Example 1 - Revenue and profit

Comparing the outcomes shows that the only profitable configurations are those which maximize the NPV or maximize the overall profit respectively. However, from an investment point of view (i.e. $NPV > 0$) the only viable solution is configuration 1. Furthermore, the achieved revenues are equal in all scenarios, with the exception of the second one: here, the objective is to minimize the overall cost of the SC and as a result, the bigger part of provided electricity is actually imported. This leads to a lower revenue and subsequently to less profits.

Examining the NPV maximization scenario more detailed shows that the major part of expenses is acquired by variable costs of raw material collection and production. Fix cost of assets as well as transportation cost is comparable low.

This example does not aim to evaluate a complex BSC, it simply shall give the reader a first idea about the model presented in this work. The results show that the material flows happen as intended and that it follows the mathematical formulation presented in the previous section. This can be observed by tracking and comparing the material flows with their respective capacity expansions as well as raw material decrease and increase.

## 5.2 Illustrative Example 2

The second illustrative example is slightly more complex. It is an extension of the first example, adding a second plant as well as a second supply and demand location.

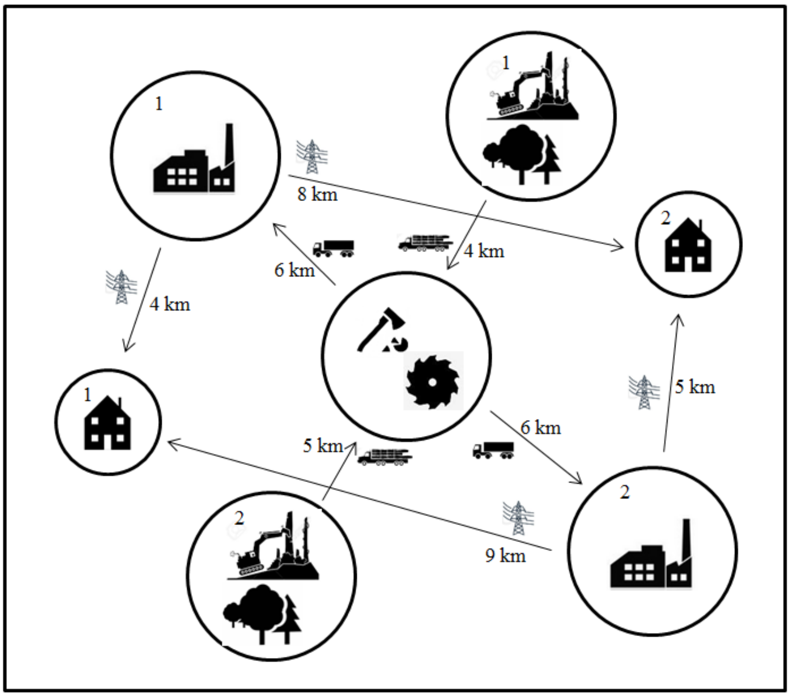


Figure 4: Second illustrative example: forest wood biomass supply chain

### 5.2.1 BSC configuration

The extended example is illustrated in Figure 4. This BSC network comprises of the following nodes:

- Facility locations (7): *locRaw1, locRaw2, locChipper, locPlant1, locPlant2, locMarket1, locMarket2*
- Tasks (6): *harvesting, transportation, chipping, combustion, distribution, storing*
- Equipment technologies (6): *harvester, truck, plant, chipper, grid, storage*
- Materials (3): *wood, woodchips, electricity*

The assumptions regarding stated in section 5.1.1 are applicable with the following differences: Technology *plant* can be installed in both *locPlant1* and *locPlant2*. All supply sites can deliver raw material to the *chipper*, of which the pre-processed feedstock can be distributed to both *plants*. Finally, both *plants* can serve any of the demand locations.

### 5.2.2 Input data and expectations

The input data of the current example has been improved compared to the previous one: it is leaned to the following case study. Both markets have a different electricity demand, also, the raw material sites host a different quantity of wood. The considered discount rate is 15%, keeping the same planning horizon of five years. Unitary electricity prices slightly differ: €0.115/kWh sold and €0.18/kWh imported.

The same four scenarios as described for the previous example (cf. 5.1.2) are considered. With additional potential facility sites, the expectation of applying illustrative example 2 is to determine, which facilities are installed and in which amount are used. For instance, it might be economically more attractive to only use one supply site to feed one or two plants; or to install plants with different capacities and.

### 5.2.3 Results and discussion

In terms of capacity installation, the results are similar to the first illustrative example: equipment is installed at all sites. However, *plant1* only supplies *locMarket1* with electricity, *plant2* only *locMarket2*.

Tables 11 and 12 compare result values of four decision variables between the four scenarious. Tables 13, 14, 15 and 16 concentrate on the NPV maximization scenario and presents its detailed results.

It can be observed that the figures have a more constant nature compared to ex. 1. Again, the minimum cost scenario does not consider installing any equipment and rather

|  | NPV | Revenue | Cost | Profit |
|---|---|---|---|---|
|  | M€ | M€ | M€ | M€ |
| $MAX_{NPV}$ | 1.302 | 920,000 | 5.234 | 3.967 |
| $MIN_{Cost}$ | -12.676 | 0 | 0 | -13.6 |
| $MAX_{Revenue}$ | -3.110 | 9.200 | 5.752 | 3.448 |
| $MAX_{Profit}$ | -0.119 | 9.200 | 5.200 | 3.999 |

Table 11: Illustrative Example 2 - Results comparison (Economics)

|  | Collected wood | Prod. power | Imported power |
|---|---|---|---|
|  | t | GWh | GWh |
| $MAX_{NPV}$ | 53,333 | 80 | 0 |
| $MIN_{Cost}$ | 0 | 0 | 80 |
| $MAX_{Revenue}$ | 53,333 | 80 | 0 |
| $MAX_{Profit}$ | 45,600 | 80 | 0 |

Table 12: Illustrative Example 2 - Results comparison (Material)

| Equipment | Location | Installed capacity (h) |
|---|---|---|
| harvester | locRaw1 | 1,333.33 |
| harvester | locRaw2 | 0 |
| chipper | locChipper | 1,333.33 |
| truck | locChipper | 1,333.33 |
| plant | locPlant1 | 6,666.67 |
| plant | locPlant2 | 6,666.67 |

Table 13: Illustrative Example 2 - Installed capacity

| Period | Inv. cost (€) | Fix cost (€) |
|---|---|---|
| t0 | 1,823,333.33 | 142,857.16 |
| t1 |  | 86,666.66 |
| t2 |  | 86,666.66 |
| t3 |  | 86,666.66 |
| t4 |  | 86,666.66 |

Table 14: Illustrative Example 2 - fixed and investment cost

| Period | Raw material (€) | Production (€) | Transportation (€) |
|---|---|---|---|
| t0 | 0 | 0 | 0 |
| t1 | 533,333.33 | 133,386.66 | 533,333.33 |
| t2 | 533,333.33 | 133,386.66 | 533,333.33 |
| t3 | 533,333.33 | 133,386.66 | 533,333.33 |
| t4 | 533,333.33 | 133,386.66 | 533,333.33 |

Table 15: Illustrative Example 2 - variable cost

| Period | Revenue (€) | Cost (€) | Profit (€) |
|---|---|---|---|
| t0 | 0 | 142,857 | -86,666.66 |
| t1 | 2,300,000 | 1,286,720 | 1,013,280 |
| t2 | 2,300,000 | 1,286,720 | 1,013,280 |
| t3 | 2,300,000 | 1,286,720 | 1,013,280 |
| t4 | 2,300,000 | 1,286,720 | 1,013,280 |

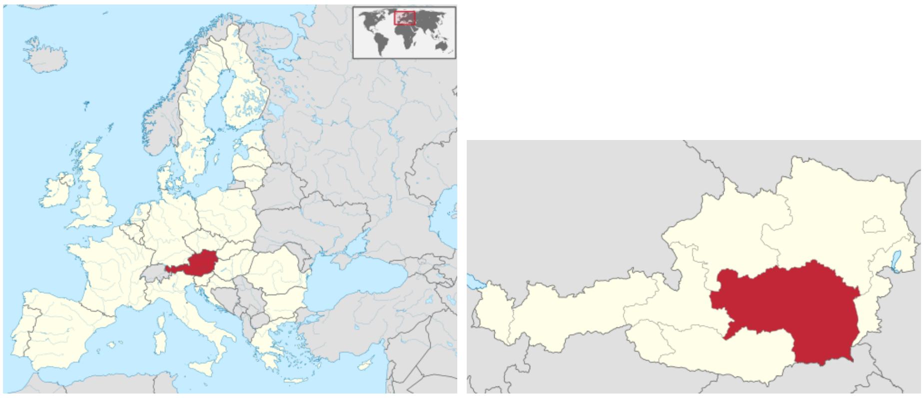
Table 16: Illustrative Example 2 - revenue and profit

# 6 Case study: A forest wood based BSC for electricity generation in Austria

The following case study was developed to be applied to the BSC model. This chapter describes the outline, location, configuration and assumptions as well as input data for the case study. The GUI is demonstrated using the case study input data and furthermore, results are presented and discussed.

## 6.1 Location

The BSC optimization model is applied to the political district *Liezen* in the state of *Styria (Steiermark)*, country of *Austria*.



(a) Austria in Europe

(b) Styria in Austria

Figure 5: Location of Styria

The Liezen district comprises of 51 communities on a total area of $3,268.26 km^2$. The population in 2015 was 79,535, resulting in a population density of $24/km^2$. A map of Styria's population density is shown in Fig. 14, Appendix C.1. (Landesstatistik Steiermark, 2013). It is the largest of all Styrian districts and located in the north-western part of the state (refer to figures 5 and 6).

Figure 6: The district of Liezen and its communities

74.8% of Liezen's area is covered by forests, which after neglecting protected areas leaves a usable forest area of 80,000 ha, containing 326 Vfm/ha of timber. (Fachabteilung 10C Forstdirektion, 2009)

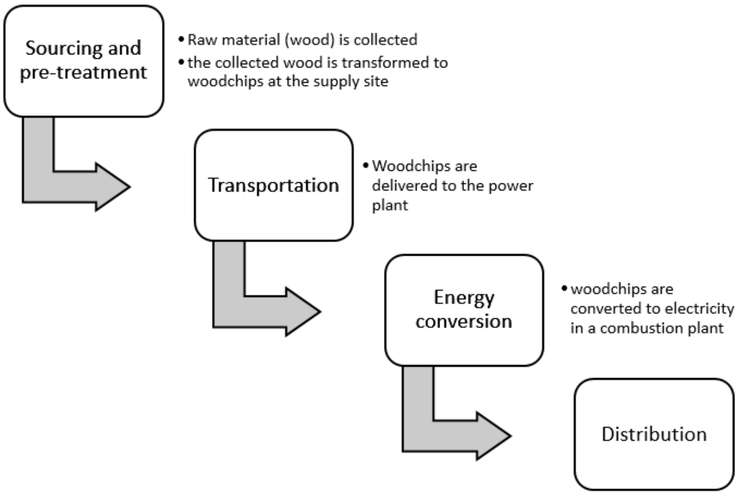


Figure 7: Process overview

### 6.1.1 Potential analysis

A potential analysis was carried out by the Austrian Institute for land usage planning in cooperation with the Energy Economics Group (EEG) of Vienna University of Technology in order to determine potentials of biomass based electricity generation. (OeIR, 2010) The authors show that in a scenario of maximum usage until 2020, Liezen is capable of providing more than 1,000 GWh/year of raw energy based on forestry, which can be converted to higher class energy carriers.

## 6.2 Configuration of the BSC

The BSC as shown in Fig. 2 is considered for this case study. It is configured as depicted in Fig. 7: a single type of raw material, forest wood, is chipped at the supply location from where it is transported to the power plant. The power plant is connected to the demand area by a medium voltage power line.

### 6.2.1 Sites

The district of Liezen has been divided into 11 aggregated demand areas based on population density. Furthermore, 5 aggregated raw material supply sites have been chosen based on publicly available GIS data[7]. 10 possible locations for power plant installations were chosen with the objective of being road accessible and located near to both supply and demand locations. A list of all locations and their purpose can be found in Table 17, also illustrated in a map (Fig. 8, larger view in Appendix C.2). Note that demand locations are denoted by a purple crystal, supply locations with red trees and plant locations with red pins.

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[7] http://www.gis.steiermark.at/

Figure 8: Map with potential BSC locations

| Demand areas | Facility locations | Supply areas |
|---|---|---|
| *demAusseerland* | *badaussee* | *raw2* |
| *demTauplitz* | *badmitterndorf* | *raw3* |
| *demDachstein* | *irdning* | *raw4* |
| *demGroebming* | *groebming* | *raw5* |
| *demIrdning* | *liezen* | *raw8* |
| *demPlanneralm* | *selzthal* | |
| *demLiezen* | *admont* | |
| *demRottenmannTrieben* | *trieben* | |
| *demAdmontGesaeuse* | *gallen* | |
| *demMooslandl* | *palfau* | |
| *demWildalpen* | | |

Table 17: Potential BSC locations

| Index | Set | Values |
|---|---|---|
| i | Tasks | *collection*, *transportation*, *chipping*, *combustion*, *distribution* |
| j | Equipment | *harvester*, *truck*, *plant*, *chipper*, *grid* |
| m | Materials | *wood*, *woodchips*, *electricity* |
| s | Service suppliers | *supplyraw*, *supplyprod*, *supplytrans* |
| t | Planning periods | *t0*, *t1*, ..., *t15* |

Table 18: Sets for the case study

### 6.2.2 Other key domains

Table 6.2.2 lists the considered sets used in case study model.

The subset data follows the same principles as already shown for the illustrative examples (cf. section 5). The *harvester* is assumed to be a hybrid equipment, being capable of harvesting and loading a chipper (forwarding).

### 6.2.3 Assumptions and miscellanous data

The following assumptions were made:

- Raw material and electricity sales/import prices are constant
- The final product demand is constant in each area
- Supply services are provided to a constant price
- Fixed cost of equipment is constant
- Re-growing of raw material is constant
- All available raw materials may be collected ($R^{max} = 1$)
- The target are does not host any facilities or distribution networks which can be made use of ($\kappa^0 = 0$)
- Storage is not considered as an option
- Distances between plant and market locations are measured linearly (airline)
- Transportation distances are measured linearly, but approximated to roads; a tortuosity factor of $\tau = 1.5$ is therefore introduced
- Tasks are regarded as ideal ($\alpha = \beta = 1$) with the exception of combustion, where $\alpha$ and $\beta$ are used to convert units and take the plant efficiency into account (discussed below)
- All raw materials enter the BSC at average properties (e.g. moisture content, heating value) and those properties do not change
- A discount rate of 10% is used

## 6.3 Input Data

In this section, the data acquisition is described.

| Division | Area (ha) | $R^0$ (t) |
|---|---|---|
| raw2 | 10,000 | 1,548,500 |
| *raw3* | 25,000 | 3,871,250 |
| *raw4* | 23,000 | 3,561,550 |
| *raw5* | 7,000 | 1,083,950 |
| *raw8* | 15,000 | 2,322,750 |

Table 19: Raw material stock initially available in supply divisions

## 6.4 Raw material

The stock of usable timber was calculated using official GIS data[8]. First, the forest area (considering only applicable forest categories) in the aggregated raw material supply division is determined (in hectares). For the Liezen district, 1 ha of forest contains 326 Vfm of wood and the annual growth is 6.8 Vfm/ha (Fachabteilung 10C Forstdirektion, 2009), leading to a relative growth of 2% per year ($\Delta R = 0.02$) . 1 Vfm represents 475 kg of established average wood (value is taken from (Landwirtschaftskammer Steiermark, 2014) and confirmed by numerous sources as standard conversion factor in the bioenergy sector). The average price in 2014 for one Vfm of round wood in Styria was € 101.79, which corresponds to a price of $\chi^{raw} = €48/t$.

The results are presented in table 6.4.

## 6.5 Electricity price and planning horizon

The Austrian government subsidies renewable energy and therefore bioenergy projects: The Ökostromgesetz (green energy law) guarantees a fixed feed-in tariff for a duration of 15 years (Legal information system, 2015). Hence, the electricity sales price in this case study is chosen to be $\rho^{sale} = €0.14/kWh$ and the planning horizon is set to 15 years.

Imports of electricity from the grid are charged with an estimated average standard price for industrial users of $\rho^{imp} = €0.18/kWh$. (E-Control Austria, 2015b)

## 6.6 Demand

Based on population density and area, the demand was roughly estimated (cf. Table 20).

## 6.7 Equipment

Equipment capacity and cost data was determined and is listed in Table 6.7. The section also presents the calculations of those values for each equipment technology.

For all types of machines, a capacity increment limit at each site was set:

- Harvester, Chipper, Truck: 10 units/year
- Plant: 5 units/year or $5MW_{el}$ installed

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[8] http://www.gis.steiermark.at/

| Market area | Demand (GWh) |
|---|---|
| *demAusseerland* | 5 |
| *demTauplitz* | 3 |
| *demDachstein* | 5 |
| *demGroebming* | 5 |
| *demIrdning* | 3 |
| *demPlanneralm* | 3 |
| *demLiezen* | 5 |
| *demRottenmannTrieben* | 5 |
| *demAdmontGesaeuse* | 3 |
| *demMooslandl* | 2 |
| *demWildalpen* | 2 |

Table 20: Electricity demand

|  | $\chi^{pr}$ | $\chi^{tr}$ | $\chi^{J}$ | $\Psi^{Asset}$ | $\theta$ | $\theta^{min}$ | $\Delta\kappa^{lim}$ |
|---|---|---|---|---|---|---|---|
|  | €/h | €/(t km) | €/h | €/h | h/t | p.u. | h/a |
| Harvester | 11.23 | - | 0 | 82.192 | 0.1404 | 0.85 | 29,200 |
| Chipper | 9.09 | - | 0 | 11.896 | 0.1818 | 0.85 | 29,200 |
| Truck | - | 6.5 | 0 | 34.247 | 0.1 | 0.5 | 29,200 |
| Plant | 5.76 | - | 5.30 | 176.67 | 1.44 | 1 | 43,800 |

Table 21: Equipment Data Overview

### 6.7.1 Harvester, Chipper, Truck

The purchase cost of a Hybrid Harvester which performs wood collection and forwarding to the chipper is rated with €240.000, productivity of 15 solid $m^3/h$ (corresponds to 7.125 t/h[9]) at an hourly cost of €80. (Valter Francescato and Zuccoli Bergomi, 2008) Hence, the capacity utilisation rate can be expressed with $\theta = 0.1404h/t$, the cost per tonne is €11.23 or an hourly cost of $\chi^{prod} = 1.576$€/h. This also includes maintenance and operation cost (therefore $\chi^{J} = 0$). The working hours are assumed with 8h/day or 2,920/year, leading to an investment cost of $\Psi^{Asset} = 82.192$€/h.

Following the same steps and sources, data is collected for a *Medium power chipper* (purchase cost €35,000, productivity 5t/h, hourly cost €50/h). (Harrill and Han, 2012) rate chipping cost with $9.95/t, which roughly corresponds to the calculated values. They state a minimum capacity utilisation rate of 85% ($\theta^{min} = 0.85$).

Finally, a *truck for woodchips transport* at a purchase cost of €100,000, loading capacity of 20t and hourly cost of €65/h is considered, with an estimated productivity of 10t/h.

### 6.7.2 Plant

The following plant was modelled to represent 1 MW of installed electrical capacity with an efficiency of 42%.

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[9] 1 $m^3 = 475$ kg

(Koppejan, 2012) proposes investment costs of approximately €650,000 per $MW_{th}$ for a plant of nominal thermal capacity of 1.5 MW (efficiency considered). Production costs are rated with €0.004 per $kWh_{el}$. (IRENA, 2012) (EnergiNet.DK, 2012)

The energy content of 1t of dry woodchips (moisture content 30%) is 12.35GJ (Koppejan, 2012), which converts to 1,440 $kWh_{el}$ considering efficiency. This is also the mass fraction value taken for $\alpha$. At assumed operating hours of 24h/day, the following cost configuration was determined:

- Investement cost $\Psi^{Asset} = 176$€/h
- Fixed cost $\chi^{J} = 5.30$€/h
- Production (variable) cost $\chi^{pr} = 5.76$€/t
- Capacity utilisation rate $\theta = 1.44$ h/t

## 6.8 Results

The case study was solved using the developed GUI in conjunction with GAMS 24.4/CPLEX 11, on an Intel Core i5-4300U CPU @ 2.50GHz. This section presents and discusses the results.

### 6.8.1 Different Objectives

As an entry point, the problem is solved in four different scenarios (similar to the illustrative examples, cf. section 5.1.2). The comparison is shown in tables 22 and 23. The outcome is comparable to the previously discussed examples: the objective of maximizing the NPV creates a BSC configuration which is economically viable and highlights the significant difference of the four objectives even more.

| | NPV | Revenue | Cost | Profit |
|---|---|---|---|---|
| | M€ | M€ | M€ | M€ |
| $MAX_{NPV}$ | 0.004 | 5.908 | 8.610 | 2.702 |
| $MIN_{Cost}$ | -25.257 | 0 | 0 | -10.524 |
| $MAX_{Revenue}$ | -27.876 | 19.134 | 8.610 | -10.524 |
| $MAX_{Profit}$ | -19.022 | 5.279 | 8.610 | 3.331 |

Table 22: Case study objectives comparison (Economics)

| | Coll. wood | Prod. power | Imp. power |
|---|---|---|---|
| | 1000 t | GWh | GWh |
| $MAX_{NPV}$ | 427 | 615 | 0 |
| $MIN_{Cost}$ | 0 | 0 | 615 |
| $MAX_{Revenue}$ | 443 | 615 | 0 |
| $MAX_{Profit}$ | 443 | 615 | 0 |

Table 23: Case study objectives comparison (Materials)

| Equipment | Location | Inst. capa. | Capa./year | Units |
|---|---|---|---|---|
| harvester | raw2 | 1,750 | 2,920 | 0.599 |
| | raw4 | 1,264 | 2,920 | 0.433 |
| | raw5 | 583 | 2,920 | 0.200 |
| | raw8 | 389 | 2,920 | 0.133 |
| truck | raw2chip | 1,250 | 2,920 | 0.428 |
| | raw4chip | 903 | 2,920 | 0.309 |
| | raw5chip | 417 | 2,920 | 0.143 |
| | raw8chip | 278 | 2,920 | 0.095 |
| chipper | raw2chip | 2,250 | 2,920 | 0.771 |
| | raw4chip | 1,625 | 2,920 | 0.557 |
| | raw5chip | 750 | 2,920 | 0.257 |
| | raw8chip | 500 | 2,920 | 0.171 |
| plant | badmitterndorf | 18,000 | 8,760 | 2.055 |
| | irdning | 6,000 | 8,760 | 0.685 |
| | selzthal | 10,000 | 8,760 | 1.142 |
| | admont | 3,000 | 8,760 | 0.342 |
| | palfau | 4,000 | 8,760 | 0.457 |

Table 24: Case study - installed capacities

Running the GUI will crate output data collections for each objective in both XLS[10] and GDX[11] formats. Additionally, charts of the main results are produced (see Figure 17 in Appendix C.4).

The following sections only discuss the results of the NPV maximization objective.

### 6.8.2 Installed facilities

Table 24 shows the magnitude of installed equipment types in each location.

A map showing the resulting material flows is shown in 9, a larger view can be found in Appendix C.3. If a site is not considered in any material flows, it is not installed.

### 6.8.3 Cost and Profit

Asset investment costs, total cost of operation (fixed + variable), profit and revenue of each period are listed in Table 6.8.3. The variable cost can be split into costs for raw material (collection and forwarding), production services (i.e. chipping and combustion) as well as transportation (Table 27)

### 6.8.4 Raw material stock

Table 28 presents the stock changes of raw materials over time.

---

[10] Microsoft Office Excel

[11] GAMS Data Exchange

| Task | Equipment | Origin | Destination |
|---|---|---|---|
| collection | harvester | raw2 | raw2chip |
| | | raw4 | raw4chip |
| | | raw5 | raw5chip |
| | | raw8 | raw8chip |
| transportation | truck | raw2chip | badmitterndorf |
| | | raw4chip | selzthal |
| | | raw4chip | admont |
| | | raw5chip | irdning |
| | | raw8chip | palfau |
| chipping | chipper | raw2chip | raw2chip |
| | | raw4chip | raw4chip |
| | | raw5chip | raw5chip |
| | | raw8chip | raw8chip |
| combustion | plant | badmitterndorf | badmitterndorf |
| | | irdning | irdning |
| | | selzthal | selzthal |
| | | admont | admont |
| | | palfau | palfau |
| distribution | grid | badmitterndorf | demAusseeerland |
| | | badmitterndorf | demTauplitz |
| | | badmitterndorf | demDachstein |
| | | badmitterndorf | demGroebming |
| | | irdning | demIrdning |
| | | irdning | demPlanneralm |
| | | selzthal | demLiezen |
| | | selzthal | demRottenmannTrieben |
| | | admont | demAdmontGesaeuse |
| | | palfau | demMooslandl |
| | | palfau | demWildalpen |

Table 25: Case study - Material flows

Figure 9: Case study established material flows

| Year | Investment | Cost | Profit | Rev |
|---|---|---|---|---|
|  | M€ | M€ | M€ | M€ |
| t0 | 13,549 | 0,217 | -0,217 | 0,000 |
| t1 | 0,000 | 3,924 | 1,816 | 5,740 |
| t2 | 0,000 | 3,924 | 1,816 | 5,740 |
| t3 | 0,000 | 3,924 | 1,816 | 5,740 |
| t4 | 0,000 | 3,924 | 1,816 | 5,740 |
| t5 | 0,000 | 3,924 | 1,816 | 5,740 |
| t6 | 0,000 | 3,924 | 1,816 | 5,740 |
| t7 | 0,000 | 3,924 | 1,816 | 5,740 |
| t8 | 0,000 | 3,924 | 1,816 | 5,740 |
| t9 | 0,000 | 3,924 | 1,816 | 5,740 |
| t10 | 0,000 | 3,924 | 1,816 | 5,740 |
| t11 | 0,000 | 3,924 | 1,816 | 5,740 |
| t12 | 0,000 | 3,924 | 1,816 | 5,740 |
| t13 | 0,000 | 3,924 | 1,816 | 5,740 |
| t14 | 0,000 | 3,924 | 1,816 | 5,740 |
| t15 | 0,000 | 3,924 | 1,816 | 5,740 |
| TOTAL | 13,549 | 59,082 | 27,018 | 86,100 |

Table 26: Case Study Economical data per period

| Period | Raw material | Production | Transportation |
|---|---|---|---|
| M€ | M€ | M€ | M€ |
| t0 | 0 | 0 | 0 |
| t0 | 0,000 | 0,000 | 0,000 |
| t1 | 0,255 | 1,367 | 2,085 |
| t2 | 0,255 | 1,367 | 2,085 |
| t3 | 0,255 | 1,367 | 2,085 |
| t4 | 0,255 | 1,367 | 2,085 |
| t5 | 0,255 | 1,367 | 2,085 |
| t6 | 0,255 | 1,367 | 2,085 |
| t7 | 0,255 | 1,367 | 2,085 |
| t8 | 0,255 | 1,367 | 2,085 |
| t9 | 0,255 | 1,367 | 2,085 |
| t10 | 0,255 | 1,367 | 2,085 |
| t11 | 0,255 | 1,367 | 2,085 |
| t12 | 0,255 | 1,367 | 2,085 |
| t13 | 0,255 | 1,367 | 2,085 |
| t14 | 0,255 | 1,367 | 2,085 |
| t15 | 0,255 | 1,367 | 2,085 |

Table 27: Case Study Economical data per period - variable cost

| Year | raw2 | raw3 | raw4 | raw5 | raw8 |
|---|---|---|---|---|---|
| | 1000 t | 1000 t | 1000 t | 1000 t | 1000 t |
| t0 | 1,425 | 3,563 | 3,278 | 998 | 2,138 |
| t1 | 1,455 | 3,637 | 3,346 | 1,018 | 2,183 |
| t2 | 1,472 | 3,712 | 3,406 | 1,035 | 2,224 |
| t3 | 1,489 | 3,786 | 3,465 | 1,052 | 2,266 |
| t4 | 1,506 | 3,860 | 3,524 | 1,068 | 2,308 |
| t5 | 1,524 | 3,935 | 3,584 | 1,085 | 2,350 |
| t6 | 1,541 | 4,009 | 3,643 | 1,102 | 2,392 |
| t7 | 1,558 | 4,083 | 3,702 | 1,118 | 2,434 |
| t8 | 1,575 | 4,158 | 3,762 | 1,135 | 2,475 |
| t9 | 1,593 | 4,232 | 3,821 | 1,151 | 2,517 |
| t10 | 1,610 | 4,306 | 3,881 | 1,168 | 2,559 |
| t11 | 1,627 | 4,381 | 3,940 | 1,185 | 2,601 |
| t12 | 1,644 | 4,455 | 3,999 | 1,201 | 2,643 |
| t13 | 1,661 | 4,529 | 4,059 | 1,218 | 2,684 |
| t14 | 1,679 | 4,603 | 4,118 | 1,235 | 2,726 |
| t15 | 1,696 | 4,678 | 4,177 | 1,251 | 2,768 |

Table 28: Stock of wood in each supply area

### 6.8.5 Produced and distributed electricity

Table 29 finally presents the electricity produced by each plant and distributed to demand areas. The demand is fully satisfied, no additional imports are required.

| Plant | Demand area | Power (GWh) |
|---|---|---|
| badmitterndorf | demAusseeerland | 75 |
| | demTauplitz | 45 |
| | demDachstein | 75 |
| | demGroebming | 75 |
| irdning | demIrdning | 45 |
| | demPlanneralm | 45 |
| selzthal | demLiezen | 75 |
| | demRottenmannTrieben | 75 |
| admont | demAdmontGesaeuse | 45 |
| palfau | demMooslandl | 30 |
| | demWildalpen | 30 |

Table 29: Delivered electricity from plants to demand areas

# 7 Discussion and conclusions

The previous sections have proposed an approach for the initial design of a Biomass Supply Chain (BSC). Results of the case study have shown that from an economic point of view, such an installation would be viable. However, those should be analysed in a critical manner regarding assumptions and limitations made during development of this work.

## 7.1 Discussion

First of all, it is obvious that profitability and NPV of a BSC depend on a very high number of variables in all stages.

The BSC model was optimized with different objectives, for illustrative reasons. It shall be noted that minimizing cost might lead to 100% imports and not building any SC network at all (as in the case study, cf. Table 22). Formulating an NPV in this case is simply wrong, as there will be no project and hence no investements. The imports of electricity were considered in the model for the following reason: if the given demand must be fully satisfied, it shall be shown whether it is cheaper to import than building a BSC and in this very case it can also be seen as opportunity cost (i.e. in the case of cost minimization). The illustrative examples however have shown that imports can supplement the difference between own production and demand.

The assumed limitation that no facilities which can be made use of initially exist was introduced on purpose, with the motive of trying to establish a BSC from scratch: if there is any viable solution in that manner, any extension and usage of existing facilities is assumed to be implicitly viable too. Co-firing of wood products in existing plants was not considered consequently and furthermore due to the fact that this technology itself comes with a high number of dependencies.

In the case study, storage was not considered as an option: the granularity of planning periods was too big to consider such activities. However, storage is an important task that needs to be introduced for subsequent scheduling. Storing for continuous input (or even for drying) can make a BSC less exposed to unforeseen events.

Raw material is a crucial factor for BSC planning: it was assumed that prices of raw material as well as the sourcing process create unique and constant cost. Putting aside that the model region hosts more than enough timber resources, the topological characteristics of Liezen (or Austria and the Alpine region in general) have a severe impact on sourcing cost. The accessibility to supply areas influences the time factor, equipment capabilities and overall results in high fix and variable cost for the sourcing steps (harvesting, sawing, forwarding). For the case study, a hybrid harvester was considered in combination with supply-site-chipping (making the forwarding step obsolete). This is a very brave simplification, given the above mentioned considerations and might not be practicable everywhere. Also, the distance from harvesting side to the nearest road could be long, too.

The wood price is, naturally, subject of fluctuations. The price volatility of wood resources is in an accessible range (Kristöfel et al., 2014), however, bioenergy is a young and immature market, which makes the raw material price an uncertainty factor that is to be taken into account for additional works. Finally, properties of wood have a significant influence on supply chain operations. Seasonal fluctuations as well as the uncertainty of weather conditions and the altitude of forests make moisture content an important uncertainty factor. This was neglected in the formulation for simplicity reasons, but is definitely to be considered in future works and was already treated in previous works such as **??**. Possible technologies to reduce moisture content are active drying or passive drying (storage). Also, the diversity of forestry brings together a high variety of different types of wood with changing heating values.

Electricity demand was estimated for the case study: the magnitude was roughly scaled to population density, since it was assumed that there is always a demand for electricity. This is a valid assumption given that Austria is not fully independent of imports. (E-Control Austria, 2015a) However, a constant demand over 15 years is unlikely; the impact of demand increase on the SC design might or might not be negligible. Existing plants and distribution networks as well as currently planned or constructed plants (of all types) were not considered to keep the problem simple. Furthermore, demand should be modelled more precisely with exact locations of transformation substations or possible grid connection points. It is proposed to add feed-in nodes to the model, to which voltage line connections need to be installed for a BSC, and aggregated demand zones to which those feed-in points are connected. This also gives the opportunity to take transmitting losses (they tally to distance) into account.

Pre-processing of raw material is an important step in the BSC to make the material suitable for both transportation and final processing. The Liezen case study regarded only one type: chipping. In order to keep transportation distances and cost slow, chipping directly at the supply site (road-side chipping) was the method chosen as by Akhtari et al. (2014). Chipping is a very straight-forward mechanism, hence, the assumption of constant fix and variable cost might hold.

Looking at Table 27 shows that in terms of variable cost, transportation takes the biggest part. This is to be analysed in detail, possible solutions are: reducing the distances between facilities (i.e. installing more), reducing cost of transportation. It shall be noted that modelling transportation cost based on distance and capacity hours is not the best approach. A proposal would be to take into account road classes, speed and amount of load in combination with distances. In the current formulation, it does not matter, for which distance a truck leaves its origin site, only the capacity hours consumed do. This is fine for an initial planning study, but not precise enough for a subsequent scheduling task. The current model shall give an estimation for the required capacity hours. The results listed in Table 24 (increase capacity of trucks to ¡0.5 units) let assume that either the formulation is not proof or the input data in this matter is wrong. However, this observation matches to those in previously published works. (Kanzian et al., 2009) (Akhtari et al., 2014)

Capacity is modelled in machine hours rather than in equipment units. However, the amount of machine hours per day (and year) is known (or stated), which implicitly creates a correspondence between machine hours and numbers of units (e.g. 1 unit of chipper corresponds to 8h/day or 2,920/a).

This approach creates more flexibility for planning, however, as mentioned in context of transportation cost, might be difficult to formulate for certain equipment classes. In any case, one limitation of the model is that all variables that are bound to capacity are assumed to be linear: half of the capacity of a specific equipment generates half the cost, half productivity etc. This is to be considered and can be used for optimizing data: if for instance the results show a plant capacity expansion of 0.3 units only, the considered 1MW plant seems to be oversized. A 300 kW plant might be a better choice and needs to be introduced with appropriate cost factors.

## 7.2 Conclusions

Using an LP approach for this problem is possible, but obviously comes with restrictions. Not all involved processes and equipments in a BSC can be linearised easily. To bypass this restriction, it is, of course, possible to define sub-processes and material states as unique objects a priori. However, this generates a much more complex problem in turn.

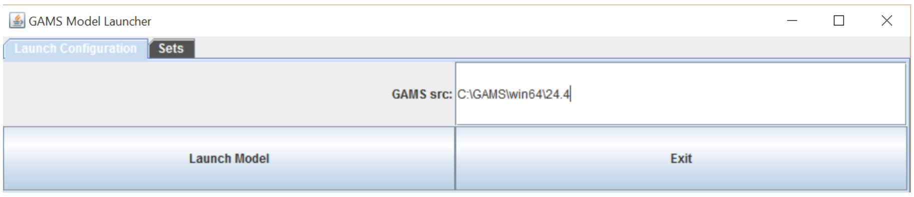
Liezen shows high potentials for BSC realizations, but due to its shape and topological conditions, the problem formulation is very complex and it might be worth considering to split the problem into smaller regions.

The model presented in this work has its limitations which were discussed in the previous sections. On the other hand, its capabilities and the fact that linearisation can make problems easier to solve was described. The BSC model can be a suitable instrument for basic initial decisions regarding planning and projecting a Biomass Supply Chain (BSC). For deeper analysis or scheduling questions, the formulations must be improved in different aspects. The most important features that are not considered but could significantly influence results and therefore decisions based on those results are pointed out and are subject for future works.

Appendices

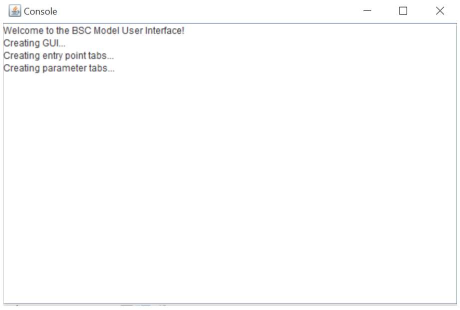
# A GUI

The GUI comprises of a main frame, built with a tabbed pane for configuring the model. A console window prints output and error messages. After running the GAMS model, an additional frame showing displaying results is opened. Figures 10, 11, 12, 13 present the GUI windows.



GAMS src: C:\GAMS\win64\24.4

Figure 10: GUI Main Frame



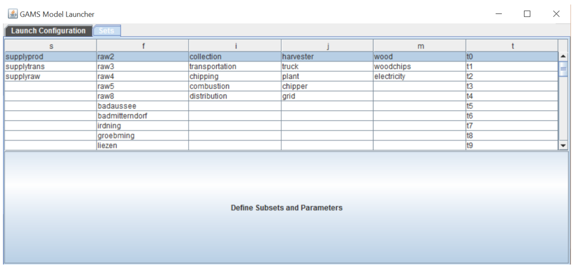
```
Welcome to the BSC Model User Interface!
Creating GUI...
Creating entry point tabs...
Creating parameter tabs...
```

Figure 11: GUI Console window

# B List of used model symbols

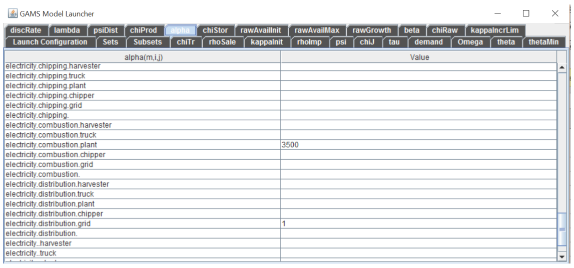
| Index | Set of |
|---|---|
| $s$ | Service suppliers |
| $f$ | Locations of facilities |
| $i$ | Tasks |
| $j$ | Equipment technologies |
| $m$ | Materials |
| $t$ | Planning periods |

Table 30: Sets (indices)



| s | f | i | j | m | t |
|---|---|---|---|---|---|
| supplyprod | raw2 | collection | harvester | wood | t0 |
| supplytrans | raw3 | transportation | truck | woodchips | t1 |
| supplyraw | raw4 | chipping | plant | electricity | t2 |
|  | raw5 | combustion | chipper |  | t3 |
|  | raw8 | distribution | grid |  | t4 |
|  | badaussee |  |  |  | t5 |
|  | badmitterndorf |  |  |  | t6 |
|  | irdning |  |  |  | t7 |
|  | groebming |  |  |  | t8 |
|  | liezen |  |  |  | t9 |

(a) GUI Main window - Sets



| alpha(m,i,j) | Value |
|---|---|
| electricity.chipping.harvester |  |
| electricity.chipping.truck |  |
| electricity.chipping.plant |  |
| electricity.chipping.chipper |  |
| electricity.chipping.grid |  |
| electricity.chipping. |  |
| electricity.combustion.harvester |  |
| electricity.combustion.truck |  |
| electricity.combustion.plant | 3500 |
| electricity.combustion.chipper |  |
| electricity.combustion.grid |  |
| electricity.combustion. |  |
| electricity.distribution.harvester |  |
| electricity.distribution.truck |  |
| electricity.distribution.plant |  |
| electricity.distribution.chipper |  |
| electricity.distribution.grid | 1 |
| electricity.distribution. |  |
| electricity..harvester |  |
| electricity..truck |  |

(b) GUI Main window - Parameters

Figure 12: Illustration of case study results with different objectives

| Subset | Indices | Description |
|---|---|---|
| $S_{pr}$ | $s$ | Service suppliers which production services |
| $S_{raw}$ | $s$ | Service suppliers which provide raw materials |
| $S_{tr}$ | $s$ | Service suppliers that provide transportation services |
| $F_s$ | $f, s$ | Locations hosting service suppliers |
| $Mkt$ | $f$ | Locations of demand (markets) |
| $Sup$ | $f$ | Locations of raw material supply |
| $J_a$ | $j, f, f'$ | Allowed flow using technology j from f to f' |
| $J_s$ | $j, s$ | Technologies available at service suppliers |
| $J_f$ | $j, f$ | Technologies which can be installed in location f |
| $J_i$ | $j, i$ | Maps technologies to their possible tasks |
| $J_w$ | $j$ | Equipments performing storage |
| $J_{fin}$ | $j$ | Equipments for final product distribution |
| $M_{fin}$ | $m$ | Materials which are final products |
| $M_{raw}$ | $m$ | Raw materials |
| $I_m$ | $i, m$ | Tasks that product material m |
| $\bar{I}_m$ | $i, m$ | Tasks that consume material m |
| $T_d$ | $i$ | Distribution tasks |
| $T_p$ | $i$ | Production tasks |

Table 31: Subsets

Figure 13: GUI Console window

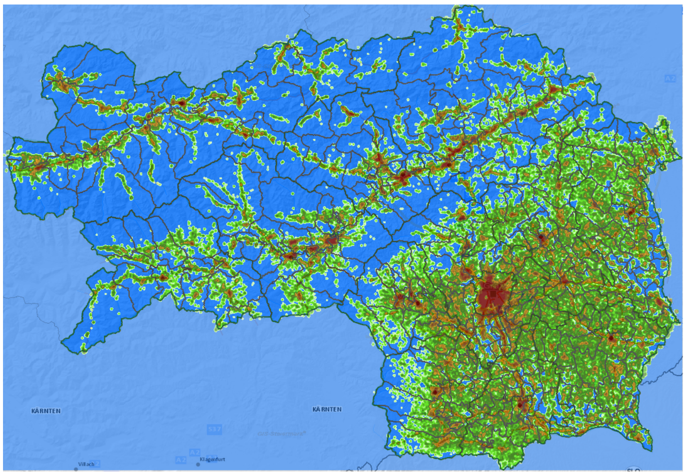


Figure 14: Population density in Styria (source: GIS Stmk.

# C Case study related data

## C.1 Population density in of Styria

## C.2 Site locations

## C.3 Installed Site locations

## C.4 Result Charts

The charts in Figure 17 illustrate some of the discussed results of the case study.

| Parameter | Indices | Unit(s) | Description |
|---|---|---|---|
| $\alpha$ | $m, i, j$ | 1 | Mass fraction of task i producing material m using equipment j |
| $\beta$ | $m, i, j$ | 1 | Mass fraction of task i consuming material m using equipment j |
| $\chi_{pr}$ | $s, m, t$ | €/t | unitary cost of activity associated with task i performed in equipment j at location f provided by supplier s |
| $\chi_{st}$ | $s, m, t$ | €/t | unitary cost of activity associated with storage task the stock of material m at location f provided by supplier s during period t |
| $\chi_{tr}$ | $s$ | €/(t km) | unitary cost of transporation activity per unit distance at supplier s in period t |
| $\chi_{raw}$ | $s, m, t$ | €/t | unitary cost of raw material m offered by supplier s in period t |
| $Dem$ | $m, f, t$ | kWh | Demand of final product m in market f during period t |
| $r$ |  | p.u. | Discount rate |
| $\lambda$ | $f, f'$ | km | Distance between f and f' |
| $\chi_j$ | $j, f$ | €/h | Fixed unitary cost per capacity of technology j in site f |
| $\Psi$ | $j, f$ | €/h | Investment cost for capacity j increment at site f |
| $\Psi_{dist}$ | $m$ | €/km | Investment cost for a final product m distribution network per length unit |
| $\Delta\kappa^{lim}$ | $j, f$ | h | Limit of capacity j increment at site f |
| $\kappa^0$ | $j, f$ | h | Capacity of equipment j initially available at site f |
| $\omega$ |  | 1 | Sufficiently large integer number |
| $\rho^{sale}$ | $m, f$ | €/kWh | Sales price of final product m in demand area f |
| $\rho^{imp}$ | $m, f$ | €/kWh | Price of imported final product m in demand area f |
| $R^0$ | $m, f$ | t | Amount of raw material m initially available at supply site f |
| $R^{max}$ | $m, f$ | p.u. | Max. permitted raw material m collection in p.u. from supply site f |
| $\Delta R$ | $m, f$ | p.u. | Per-period growth of raw material m at supply site f, in p.u. of initially available stock |
| $\theta$ | $j, i$ | h/t | Utilization rate of equipment j capacity by task i activity |
| $\theta^{min}$ | $j, f$ | p.u. | Min. utilization rate of equipment j capacity in p.u. of installed |
| $\tau$ |  | 1 | Tortuosity factor |

Table 32: Parameters

| Variable | Indices | Unit | Description |
|---|---|---|---|
| $V$ | $j, f$ | [bin] | Equipment is installed at site f |
| $Z$ | $f, f'$ | [bin] | A final product distr. network f to f' is built |
| $A$ | $i, j, f, f', t$ | t | Activity of task |
| $\Psi^{Asset}$ | $t$ | € | Fixed Assets investment cost |
| $\Psi^{imp}$ | $t$ | € | Imported final products costs |
| $Dist^{fin}$ | $t$ | kWh | Distributed final product |
| $Col^{raw}$ | $t$ | t | Amount of collected raw material |
| $Col^{raw,tot}$ | | t | Total amount of collected raw material |
| $\kappa$ | $j, f, t$ | h | Equipment capacity |
| $\Delta\kappa$ | $j, f, t$ | h | Increment of equipment capacity |
| $Imp^{fin}$ | $m, f, t$ | kWh | Amount of final product imports |
| $Imp^{fin,tot}$ | $t$ | kWh | Total amount of imported final products |
| $\Phi$ | $t$ | € | Total Supply chain cost per period |
| $\Phi^{fix}$ | $t$ | € | Fixed supply chain cost per period |
| $Purch$ | $s, t$ | € | Purchases made to suppliers |
| $Purch^{pr}$ | $s, t$ | € | Purchases made to production service supliers |
| $Purch^{rm}$ | $s, t$ | € | |
| $R$ | $m, f, t$ | t | |
| $Rev$ | $t$ | € | |
| $Sales$ | $m, f, f', t$ | € | |
| $S$ | $m, f, t$ | t | |
| $\xi$ | $j, f, t$ | p.u. | |
| NPV | | € | |
| $Phi^{tot}$ | | € | |
| $Profit$ | $t$ | € | |
| $Profit^{tot}$ | | € | |
| $Rev^{tot}$ | | € | |

Table 33: Variables

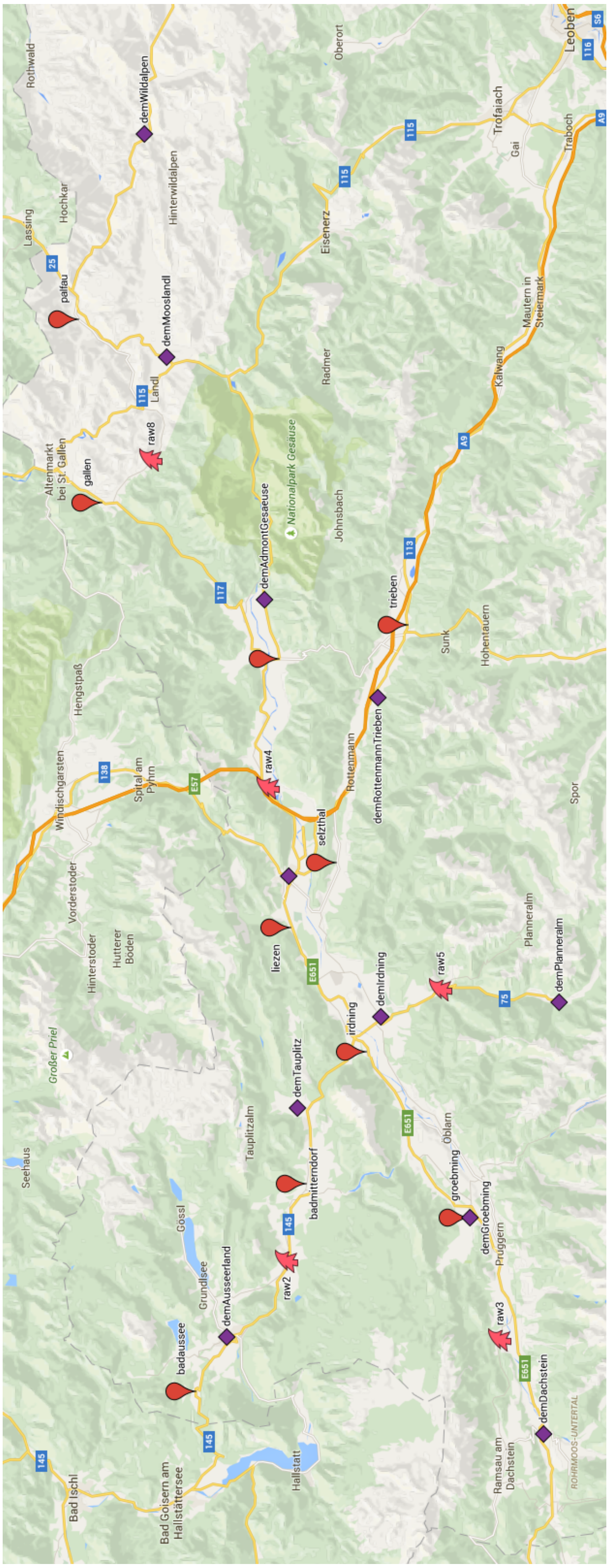


Figure 15: Map with potential BSC locations

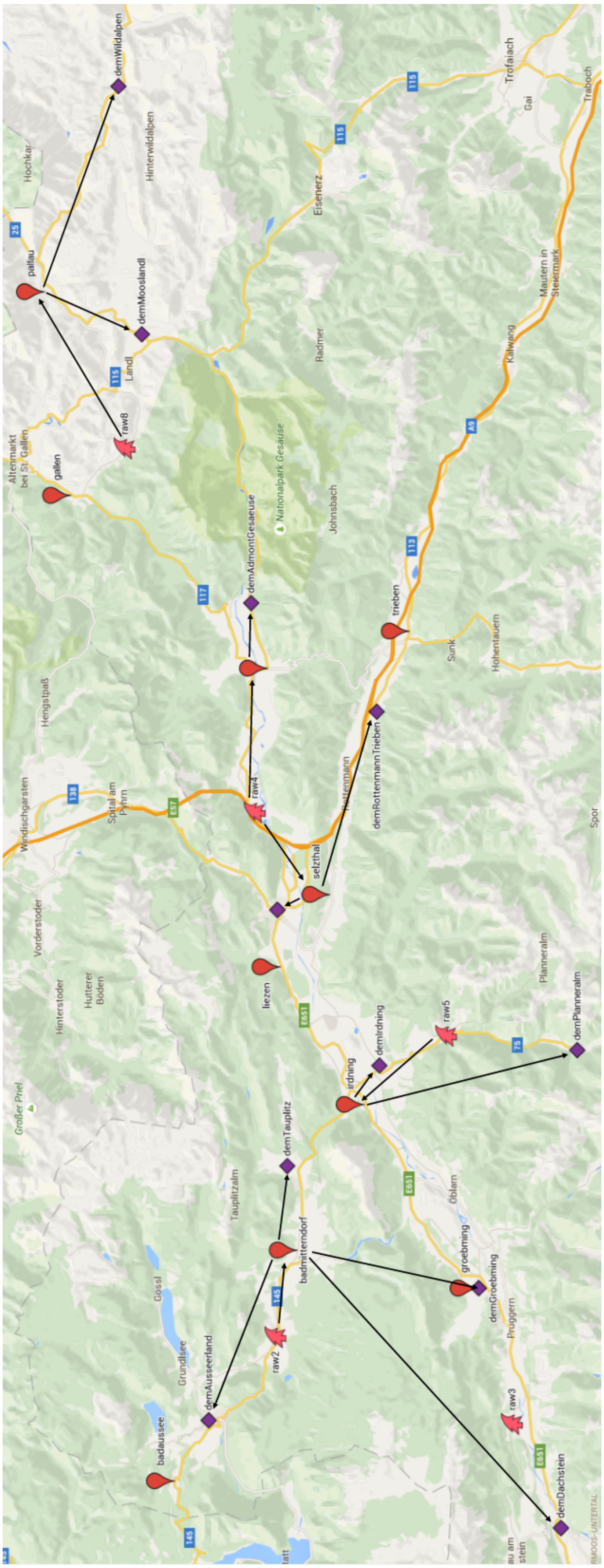
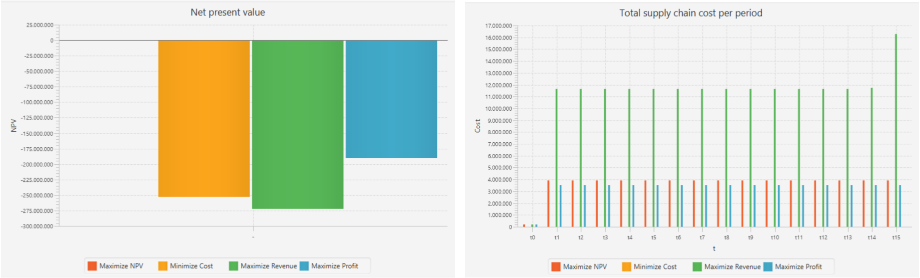
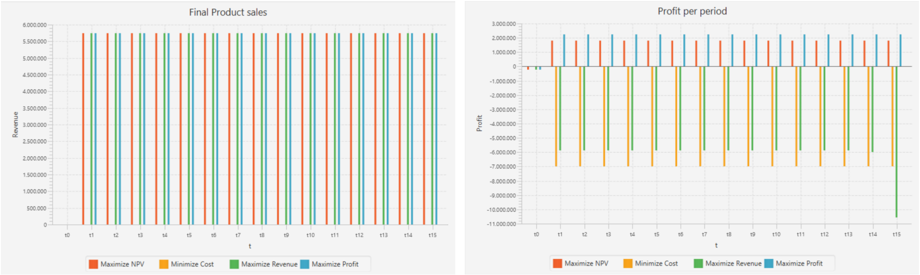


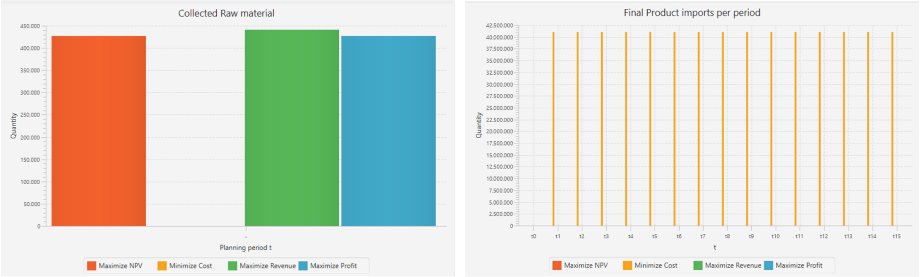
Figure 16: Installed facilities and material flows



(a) NPV (b) Cost



(c) Revenue (d) Profit



(e) Collected wood (f) Imported electricity

Figure 17: Illustration of case study results with different objectives

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# Part II

# The role and development of electricity generation from biomass in Austria and the European Union: status, potential, constraints and a policy framework to promote its development

## Abstract

In light of global warming, United Nations as well as the European Union have formulated climate and energy strategies with the long-term goal of restraining the increase of Greenhouse Gas Emissions. Consequently, those strategies had a strong impact on the EU's energy systems. Under the Renewable Energy directive, closely interrelated with the Kyoto protocol, a large policy framework to promote Renewable Energy in the EU was established by all Member States to reach national binding targets. This work presents the course of events leading those targets and analyses the differently adopted support mechanisms such as the Feed-In Tariffs. Then, the focus is put on the contribution of Biomass (in particular wood) to electricity generation, explaining its role in European energy systems, its potentials and also barriers, supported with statistical figures. Finally, the situation of Renewables and Biomass is assessed for the case of Austria. The work concludes that under existing policies, the price of carbon and the strong stake of conventional energy sources (fossil, nuclear), long term projections of Biomass contribution are impossible, making its contribution unlikely to be on a large scale.

# Contents

# List of Figures

# List of Tables

# List of acronyms

| | |
|---|---|
| **ag** | above-ground |
| **bg** | below-ground |
| **BCR** | Brussels Capital Region |
| **BMNT** | Bundesministerium fuer Nachhaltigkeit und Tourismus |
| **BMVIT** | Bundesministerium fuer Vekehr, Innovation und Technologie |
| **BRUGEL** | Brussels Regulatory Authority |
| **CWaPE** | Walloon Energy Commission |
| **CCS** | Carbon Capture and Storage |
| **CDM** | Clean Development Mechanism |
| **CfD** | Contract for Difference |
| **CHP** | Combined Heat and Power |
| $CO_2$ | carbon-dioxide |
| **CRE** | Commission de régulation de l'énergie |
| **CREG** | Federal Electricity Regulatory Authority of Belgium |
| **CSP** | Concentrated Solar Power |
| **EFISCEN** | European Forest Information SCENario |
| **ElWOG** | Elektrizitaetswirtschafts- und Organisationsgesetz |
| **EPA** | Environmental Protection Agency |
| **ESD** | Effort Sharing Decision |
| **ETS** | Emissions Trading System |
| **EU** | European Union |
| **EUROSTAT** | European Statistical Office |
| **FAO** | Food and Agriculture Organization of the United Nations |
| **FAWS** | Forest Available for Wood Supply |
| **FNAWS** | Forest Not Available for Wood Supply |
| **FIP** | Feed-in Premium |
| **FIT** | Feed-in Tariff |
| **FRA** | Forest Resources Assessment |
| **GHG** | Greenhouse Gas |
| **GIS** | Geographic Information System |
| **GO** | Guarantee of Origin |
| **IEA** | International Energy Agency |

| | |
|---|---|
| **IPCC** | Intergovernmental Panel on Climate Change |
| **JI** | Joint Implementation |
| **MS** | Member State |
| **NFI** | National Forest Inventory |
| **NREAP** | National Renewable Energy Action Plan |
| **NUTS** | Nomenclature des Unites Territoriales Statistiques |
| **OeBMV** | Oesterreichischer Biomasseverband |
| **OeMAG** | Abwicklungsstelle für Oekostrom AG |
| **OeSG** | Oekostromgesetz |
| **PSO** | Public Service Obligation |
| **PV** | Photovoltaic |
| **RE** | Renewable Energy |
| **RED** | Renewable Energy Directive |
| **RES** | Renewable Energy Source |
| **RES-E** | Electricity from Renewable Energy Sources |
| **ROI** | Return on Investment |
| **RPS** | Renewables Portfolio Standard |
| **SoEF** | State of Europe's Forests |
| **TGC** | Tradable Green Certificate |
| **toe** | tonne of oil equivalent |
| **UN** | United Nations |
| **UNFCCC** | United Nations Framework Convention on Climate Change |
| **US** | United States |
| **USA** | United States of America |
| **VAT** | Value Added Tax |
| **VREG** | Flemish Regulator of the Electricity and Gas market |

# 8 Introduction

The global atmospheric temperature is rising - a trend which triggered the world community to act. The Kyoto protocol is a widely known result of commonly agreeing on a strategy, necessary to reduce the impacts of global warming on nature and society.

The European Union always saw itself as a role model in this context, and prove it by committing to Greenhouse Gas emission reduction and Renewable Energys expansion targets, which were furthermore enacted in law and binding targets for its Member States under the Renewable Energy Directive. While conventional fossil and nuclear power still contributes largely to the worldwide energy systems, the European Union decided to rethink the energy and climate strategies in favour of Renewables and on account of conventional sources under ecological, but also political motivation.

The present work aims to present the course of events leading to the EU's climate and energy strategies, their evolutions, policy frameworks as well as national implementations on the path to promote the expansion of Renewable Energy. A second focus area is biomass, in particular its utilization for electricity generation. In the mix of Renewable Energy Sources, biomass has a somewhat special role, as it represents a diverse group material with manifold properties, holding both advantages and disadvantages compared to other Renewables and even conventional sources of energy. Nonetheless, biomass and in particular wood, is a considerably large source of Renewable Energy in Europe, which subsequent sections will show.

# 9 Origins, development and evolution of the European Union's climate & energy strategy

This section provides a view on the course of events that led from initial UN conversations to today's EU climate and energy targets. It serves as an introduction to subsequent sections, which will analyse the EU members' national binding targets and their adoptions in closer details.

## 9.1 UN conventions and EU climate targets

The EU has set targets for its member states to reduce the emissions of GHGs, progressively up to the year 2050. [1]

Following gives a view on the timeline of events: from the first EU climate target originating in the UN Intergovernmental Panel on Climate Change (IPCC) report to Kyoto, to the the *20-20-20 by 2020* strategy and beyond.[2]

### 9.1.1 UN conventions and the first European climate target

The European Union's efforts to address the earth's climate change have their origins in conversations organised by the UN. In 1990, the IPCC issued their first report; under a "Business-as-usual" scenario of man-made GHG emissions (i.e. without taking preventive measures), they predict a likely increase of the global atmospheric mean temperature of 3°C by end of the 21$^{st}$ century. (IPCC, 1990)

**The first European Climate Target** was a consequence of the IPCC report leading to the topic to be discussed the first time by the European Council in the same year, during preparation of the upcoming negotiations on the United Nations Framework Convention on Climate Change (UNFCCC). What followed was an agreement of EU leaders to maintain the 1990 levels of the European community's GHG emissions until the year 2000. (Council of the European Union, 1990)

This agreement may be regarded as the *first EU climate target* but, according to Kelly et al. (2010), it was purely indicative: the agreement did not include any notable measures or actions to be taken in order to reach its targets, nor did it assign any hard responsibilities to the Member States, but rather intended to raise awareness and for climate change

A further step followed in 1996, where the European Council stated that "global average temperature increase should not exceed 2 °C above pre-industrial level" while refining the previously agreed targets. (Council of the European Union, 1996)

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[1] https://ec.europa.eu/clima/policies/strategies_en

[2] The Intergovernmental Panel on Climate Change is the UN body for assessing the science related to climate change.

### 9.1.2 Kyoto protocol and commitments

The cornerstone of the EU commitments in Kyoto was already set upfront to the climate summit, where the EU drafted a GHG emissions reduction target of 15% compared to 1990 levels, which would be distributed among the Member States (MSs). Later on revised, this would be known as the “burden-sharing agreement”. (Kelly et al., 2010)

**The international climate summit in Kyoto** took place in December 1997. Participating industrialised countries have jointly identified a set of GHGs and committed to reducing their emissions by an average of 5% below 1990 levels during the “first commitment period” (2008-2012) in the so-called “Kyoto-protocol to the UNFCCC”. The (at the time) 15 EU Member States committed themselves to an even higher target of 8% in reductions. (United Nations, 1998)

The protocol in its final edition also describes “flexible mechanisms” which will become relevant later in this work: Emissions Trading System (ETS), Joint Implementation (JI) and Clean Development Mechanism (CDM).

**First commitment period** Formal agreements based on the commitments made in Kyoto were proposed by the European Commission in 1998, detailing the individual targets and obligations in order to reach the 8%-reduction-goal by all MSs during the first commitment period[3]. (European Commission, 1998).

In 2002, the European Council approved the proposal, which was further known as the “burden sharing agreement” (Council of the European Union, 2002) that distributed the ”burden” of the Kyoto commitments across all MSs, under consideration of their relative wealth. The quantitative targets per MS can be found in the Appendices, Table 17.

Finally, in 2004, the burden sharing agreement was promoted to binding law for all Member States, along with other mechanisms to monitor GHG emissions. The ground was set to jointly work towards the Kyoto targets. (European Parliament and Council of the European Union, 2004).

In the same year, the enlargement of the European Union brought ten additional MSs; all of them, except Cyprus and Malta, agreed to participate in the burden-sharing agreement, which was accordingly expanded. (European Commission, 2006) The 2007 and 2013 EU enlargements have included additional Eastern European MSs in the burden sharing agreement in a similar way. (European Commission, 2010) (European Commission, 2013)

## 9.2 EU climate strategies & targets

The EU continued with a progressive elaboration of climate and energy strategies, which are summarized in the following.

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[3] https://ec.europa.eu/clima/policies/strategies/progress/kyoto_1_en

### 9.2.1 2050 Long-term strategy

In 2009, the Council of the European Union reminds and calls the MSs to embrace the “2 degree objective”, i.e. maintaining the global increase of the atmospheric temperature below 2°C above pre-industrial levels (cf. section 9.1.1). Furthermore, the Council recommends to reduce global emissions for at least 80% by 2050 compared to 1990 levels. (Council of the European Union, 2009b)

**2011 - Roadmap for a competitive low-carbon Europe** A consolidated communication package was published by the European Commission in 2011, titled “A roadmap for moving to a competitive low carbon economy in 2050”.[4]

The roadmap, with the ultimate milestone of reducing the EU’s GHG emissions by 80% as per 2050, proposes progressively growing intermediate targets for emissions reductions over the years, namely 25% in 2020, 40% in 2030 and 60% in 2040. Electricity generation was identified as one of the key sectors contributing to this goal. However, the priority remains to reach the “20-20-20 by 2020” goal and the roadmap does not suggest any new 2020 targets. (European Commission, 2011)

**2018 - Vision for a competitive and climate neutral economy by 2050** Similar to the 2011 roadmap, the communication package published by the commission in 2018 does not intend to introduce new policies or binding targets, nor to revise the EU’s 2030 targets. It rather re-emphasizes the vision and strategy of the EU in the aftermath of the “Paris Agreement” (cf. section 9.4) and the IPCC’s special report on the “impacts of global warming of 1.5 degrees above pre-industrial levels” (IPCC, 2018).

The vision states that “the EU has a vital interest in working towards a net-zero GHG emissions[5] economy by mid-century” and demonstrates that “net-zero emissions can go hand in hand with prosperity, having other economies follow its successful example.” Pathways to achieve this goal are, among others: clean energy transition, not limited to further increasing RES-E and rolling out “carbon-free, connected and automated road-transport mobility”. (European Commission, 2018)

### 9.2.2 2020 climate & energy package

In light of the first commitment period approaching, the EU decision makers began working on actions for the years after this period, formulating targets for 2020. (Council of the European Union, 2007)

This set was broadly known as “20-20-20 by 2020”, with its name indicating the following main targets:

- 20% reduction of GHG emissions compared to 1990 levels
- 20% share of RES in final energy consumption
- 20% of savings/improvements in regards to energy efficiency

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[4] `https://ec.europa.eu/clima/policies/strategies/2050_en`

[5] net-zero = reduced 100%, i.e. to zero

to be reached by 2020.[6] After revisions, the final compromise of the EU leaders was formulated and published in 2008. (Council of the European Union, 2008)

In order to meet the above mentioned targets, the EU enacted them in binding legislation for the Member States in 2009, introducing a number of policies, also known as the “2020 climate & energy package”. (Council of the European Union, 2009a) The four main aspects and directives of this package are as follows:

- the ETS directive (a directive on emissions trading), cf. European Parliament and Council of the European Union (2009)
- the Effort Sharing Decision (ESD), cf. Council of the European Union and European Parliament (2009a)
- the RED, cf. (Council of the European Union and European Parliament, 2009b), see also section 9.3
- a directive on Carbon Capture and Storage (CCS) (Council of the European Union and European Parliament, 2009c)

out of which the Renewable Energy Directive (RED) will be further addressed within the scope of this work (cf. section 9.3).

It is worth mentioning that the ETS is the tool applied to large industry and power generation sectors, and covers approximately 45% of the EU’s GHG emissions, whereas the remaining 55% (non-ETS) shall be covered by the Effort Sharing Decision (ESD).

### 9.2.3 2030 climate & energy framework

In essence, the “2030 climate & energy framework”[7] is part of the 2050 long-term strategy (cf. section 9.2.1) and comprises of three key targets to be reached by 2030:

- 40% reduction of GHG emissions compared to 1990 levels
- 27% share of RESs in final energy consumption
- 27% of savings/improvements in regards to energy efficiency

All three of those targets originate in the “2020 climate & energy package” (cf. section 9.2.2) and were accordingly adapted. However, in contrast to the original package, the 2030 framework sets the RES target as only binding on EU level (i.e. they will not be translated into national targets via EU legislation). This makes the ESD a fundamentally different approach compared to the burden sharing agreement. European Commission (2014) justifies this decision with “greater flexibility for Member States” and cost-effectivity, while emphasizing that this would not invalidate the previously agreed, national (binding) targets.

As to the 40% cut in GHG emissions, the ETS sectors must reduce emissions by 43% and non-ETS sectors (MSs) by 30%, compared to their 2005 levels. (Council of the European Union, 2014)

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[6] `https://ec.europa.eu/clima/policies/strategies/2020_en`

[7] `https://ec.europa.eu/clima/policies/strategies/2030_en`

### 9.2.4 Clean energy for all Europeans - the “Winter Package”

In 2016, the EU released the “Clean Energy for all Europeans” package (European Commission, 2016), also referred to as the “Winter package”. The objective of this package was to provide additional legislative frameworks for completing the implementation of the Energy Union. In light of the 2030 goals, the RED also got a recast, with extensions and new proposals, with the objective of jointly reaching the targets (cf. section 9.2.3).

On 14 June 2018, a political agreement was achieved by EU institutions, defining a binding renewable energy target of 32% for the EU in 2030, including a clause for a revision by they year of 2023.[8]

## 9.3 The EU Renewable Energy Directive

The Renewable Energy Directive (RED), which came as part of the 2020 energy and climate package (cf. section 9.2.2), was transposed into binding national laws by all Member States (MSs), with the objective of reaching the common RES target by 2020, namely to establish a 20% share of RESs in final energy consumption.

This community target was distributed among the MSs as individual targets from between 10% (Malta) and 49% (Sweden), according to the burden sharing agreement. (Council of the European Union and European Parliament, 2009b) A complete list of the national targets is presented by Table 18 in the appendices.

### 9.3.1 National Renewable Energy Action Plans (NREAPs)

The RED, Article 4, mandated each MS to prepare a National Renewable Energy Action Plan (NREAP) and submit same to the European Commission by mid of 2010. It should set out in detail, how the MS intends to reach their specific national RES targets, and by which actions, policies and instruments, while the choice of those remains at full disposal of the MS. Furthermore, as per Article 22, the MS has to submit progress reports every second year. (Council of the European Union and European Parliament, 2009b)

**Contents** The NREAP must covers but is not limited to the following aspects:

- National energy policies and legal basis
- Energy consumption forecasts and Renewables trajectories
- Overall RES targets and the planned measures to reach them

Regarding support schemes to promote the use of Electricity from Renewable Energy Sources (RES-E), the MS is asked to provide details on:

- Regulations, legal basis, authorities and financing
- Obligations, ownership, responsibility
- Quality Audits
- Implementation details and applicability of support schemes

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[8] https://ec.europa.eu/energy/en/topics/renewable-energy

- Conditions and criteria, penalties for non-fullfillment
- Timelines
- Price minimums, averages (if applicable)

The NREAPs and their progress reports are publicly available.[9]

## 9.4 Paris agreement: 2020 and beyond

The "Paris agreement" was signed in 2016 and establishes an agreement within the UNFCCC.

Its focus lies in reducing global GHG emissions, in order to mitigate the risk of climate change impacts. Among the articles of the agreement the central long-term goals are:

- "Holding the increase in the global average temperature well below 2°C above pre-industrial levels" (this is in-line with previous long-term goals of e.g. the EU, cf. section 9.2.1)
- and to "limit the temperature increase to 1.5°C above pre-industrial levels"

In order to reach the long-term goals, each signing member is supposed to plan and monitor their contribution, and set new targets that go beyond previously set ones. It shall be noted that the agreement does not enforce any specific guidelines as to the targets or their monitoring.

The Paris Agreement becomes effective with the year 2020. (United Nations, 2015)

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[9] `https://ec.europa.eu/energy/en/topics/renewable-energy/national-action-plans`

# 10 Policies, means and instruments to support the expansion of Electricity from Renewable Energy Sources in the European Union

After an introduction of the European Union's climate and energy strategy and its timeline was provided in section 9, the following section will now align the focus closer on policies which have been implemented specifically for the purpose of increasing the share of Electricity from Renewable Energy Sources (RES-E) in accordance with the EU's vision.

As the title indicates, other sectors subject to climate policies, such as transport, heating and cooling as well as energy efficiency are beyond the scope of this work and will not be addressed.

## 10.1 An overview of common support schemes for Renewable Energy

Support schemes for Renewable Energy (RE) projects have been introduced to make Renewables cost-competitive compared to other, established energy sources, and with the objective of increasing investments in RE. In particular for RES-E, they aim to fill the gap between the costs of energy and revenues, compensating electricity plant operators. (Banja et al., 2017)

The mechanisms can be classified into price- and quantity-based approaches. Figure 1 illustrates the relation between support schemes and market price. Predominant and highly representative schemes are FIT (price-based) and quota systems, such as green certificates or a Renewables Portfolio Standard (RPS) (quantity-based). (Schallenberg-Rodriguez, 2017)

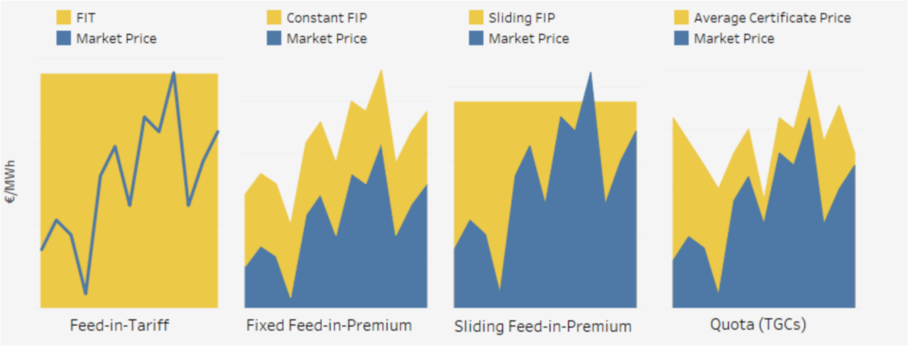

Figure 1: Schematic illustration of RES support schemes and their relation to market price (source: Banja et al. (2017))

This section shall provide a description of the most widely adopted support schemes worldwide, focusing on the main support schemes applied in the EU.

### 10.1.1 Feed-in Tariff (FIT) system

Many authors consider Feed-in Tariffs (FITs) the most effective policies serving the promotion of Electricity from Renewable Energy Sources (RES-E) (e.g. Couture and Gagnon (2010); Pietruszko (2007)).

According to Mendonça (2012), FIT policies used to be predominantly adopted in the EU, before being also observed in many other parts of the world.

FIT policies typically go in line with (1) guaranteed and prioritized grid access; and (2) long-term price guarantees or purchase agreements (15-25 years). (Couture et al., 2010)

The first European country to introduce a FIT was Germany in 1990. (Couture et al., 2010) Since that year, the number of countries which adopted such a support scheme, increased from two (USA and Germany) to 69 in 2013. (Alizada, 2018)

**The basic concept** of a FIT is: for a given period, RES-E producers are guaranteed to be paid a fixed price for each unit of energy fed into the grid. Prices (tariffs) can be oriented on the cost of installation and operation, also considering the economic lifecycle of RE technology project, and aim to provide investors with a long term contract and assurance for Return on Investment (ROI). (Barbosa et al., 2018; Couture and Gagnon, 2010)

Barbosa et al. (2018) suggest that fixed-price FIT schemes are preferred from investors point of view, as they impose a low risk and are not depending on market conditions. However, they may be designed based on imprecise forecasts, which itself could be a risk. Furthermore, regulatory uncertainty, i.e. policymakers' regular changes to the policies (e.g. adaptions market conditions, technology prices) is regarded as potential blocker for investors to sign a FIT contract or any other support scheme.

Today, FIT is the most common RE policy besides RPS, and the success is partly accounted to diffusion mechanisms such as suasion from stronger to weaker countries. (Alizada, 2018)

**Tariff design** Couture et al. (2010) suggest that among numerous choices about how to best design the tariffs, the most effective way is to orient them on recovering RE technology specific generation cost, and adding profit. This implies consideration of many cost components, including investment, operational and maintenance cost, as well as administrative and grid-related costs. (Jacobs, 2010)

Another essential design question is whether or not the tariff shall relate to the electricity market price; in this case, the model is referred to as premium-price policy (cf. 10.1.1), rather than a fixed price. Fixed price FIT were observed to be the preferred choice in the early years of RES-E promotion in the EU.

Depending on experience and the desired complexity, tariff design can foresee many differentiating aspects (technology, size, any other condition) and even a so-called tariff degression, where the granted tariff price is reduced each year. Tariff degression shall promote efficiency and considers technical progress, which in turn reduces cost over time. (Jacobs, 2010)

Commonly adopted FIT structures tend to impose the full risk to either the investor or the policy-maker, rather than share it between them. (Farrell et al., 2017) Especially fixed-price FITs enjoy popularity despite being less efficient than other instruments, as greatly reduce the investors' exposure to market price risk. (Devine et al., 2017) A counter example is the Great Britain with its Contract for Difference approach (cf. section 10.3.28), a market oriented scheme which brings benefits for both involved parties.

**Feed-in Premiums (FIPs)** In essence, the FIP is a market-oriented FIT, in that its characteristics depend on the electricity market price.

*Note: for easier differentiation, within this work, the term FIT is used for market-independent, whereas the the term FIP is used for market-dependant FITs.*

The basic FIP system consists of a guaranteed payment (the "premium") which is paid on top of the spot market price of electricity. Those premiums are granted, similar as in a FIT, for a given period, and are set to be either a constant (fixed throughout the eligibility period) or a sliding value (changing over time, adapting to the actual market conditions). (Couture et al., 2010)

Another approach is a minimum price guarantee (fixed price floor), in which the producer receives the market price for electricity, but in any case a guaranteed minimum price. (Couture and Gagnon, 2010) An extensive analysis on this design choice is elaborated by Barbosa et al. (2018).

**Criticism** A review of literature shows that there have been numerous studies and publications about the FIT concept; its advantages and disadvantages, design optimisation and best practices as well as criticism (despite the recognised positive effects on RE innovation).

Böhringer et al. (2017) state that, in the case of Germany, the cost of FIT schemes have exploded (amounts to about €26 billion in 2016), eventually leading to an increase of consumer electricity prices. Furthermore, they criticise that FITs are significantly involved in increasing the economy-wide carbon-dioxide ($CO_2$) abatement cost, and hence are regarded as inefficient policy instruments in the EU. A relation between FIT and $CO_2$ abatement cost is also studied by other authors. (Bakhtyar et al., 2017)

FIT schemes which do not per design respond to electricity market changes can shift the financial disadvantage to the end customer in certain cases, Ciarreta et al. (2017); Devine et al. (2017) suggest. Also, if not carefully designed, they may not promote efficiency and cost-savings over time. Other authors show that tariffs may lead to increased taxes and public costs, could induce windfall profits for electricity retailers and even reduce the ROI from RES-E installations. (Martin and Rice, 2017)

On the contrary, Jacobs (2010) suggest that FITs are proven to be the most successful method to promote electricity from Renewables, with their flexible design and adaption to national frameworks and objectives. Furthermore they suggest that FITs promote not only the subject of promotion itself, but also create macro-economic benefits and opens the market to actors of different size.

### 10.1.2 Quota systems

Renewables Portfolio Standards (RPSs) represent a system of incentives, in which users have quantified obligations to increase RE shares in their overall production. (Barbosa et al., 2018) In a wider context, also the RED could be classified as RPS, with the EU Emissions Trading System acting as tool for its Tradable Green Certificates (TGCs). Besides Feed-in Tariffs, quota systems are common support mechanisms applied in the EU.

In the context of electricity generation, Renewable Energy quotas generally define shares of RES in the mix of the overall produced electricity, which can be broken down into different technologies. Quota systems comprise of two concepts: (1) a quota obligation, which is assigned and represents an imposed target, and (2) a tradable unit such as a TGC (often referred to as "Green certificate"), which incorporates the physical representation of what a quota obligation stands for. (Schallenberg-Rodriguez, 2017)

A quota obligation is met by obtaining its associated certificate, either through production or trade. Missing quota obligations are penalized, while surplus generates additional income. In this concept lies the principal incentive nature of the quota system.

**Quota obligations** are assigned to electricity suppliers and large grid participants with the goal to reach specific targets, such as the RED or any other RPS. A Renewable quota represents a percentage of the provided (electricity supplier) or consumed (large electricity customer) energy that must originate from a RES.

**Green certificates** are generated by RES-E production units: for a specified amount (could be 1 MWh) of Electricity from Renewable Energy Sources fed into the grid, an electricity producer receives a TGC. Electricity suppliers or customers with obligations buy TGCs from electricity producers; those transactions fulfil obligations of the obligees, and create income for the producers.

Belgium has implemented a sophisticated quota system, serving as illustrative example (refer to section 10.3.2).

Schallenberg-Rodriguez (2017) suggest that quota systems, show advantages over FITs such as cost-efficiency and a stable development. Latter one can be justified with the fact that the obligations must be fulfilled withing a certain time frame. The authors concede that quota systems seemed to be more compatible with the expediting the electricity market liberalisation than FIT systems, but acknowledge that the success of FIT is indeed its simplicity and scalability.

Held and Ragwitz (2014) agree with Schallenberg-Rodriguez (2017), that a main advantage of quota systems (obligation vs. certificates) is their high compatibility with the principles of markets and the setting of competitive prices. Nevertheless they highlight that the policy cost may increase in case of uncertain electricity price development due to high risk premiums, or on the contrary, could also result in windfall-profits. Those phenomenons however typically appear in technology neutral quota systems, and as such can be mitigated by design.

### 10.1.3 Other schemes

Besides the main contributors FIT and quota systems, policymakers apply other schemes in order to support RES. (Schallenberg-Rodriguez, 2017)

**Tendering** systems work with public call for tenders, where potential investors participate in bidding sessions. Subject of the tenders is a defined quantity RES-E units, which are reimbursed at the marginal bidding price to the lowest bidder. Tendering is alternatively used to award any other kind of RES-E support to the bidders, e.g. a Feed-in Tariff or subsidies. As such, tendering is less a promotion scheme than a means to distribute support mechanisms through bidding conferences rather than through application and allocation.

**Net-Metering** may be used to compensate small producers (private owners) for the RES-E they feed into the grid.

**Investment subsidies and loans** may be used to support high initial investment costs of RE installation. Loans with low interest rates are an alternative form of investment subsidies. Subsidies may be granted after the first-come-first-served principle, through direct selection or public tendering.

**Fiscal instruments** can be tax regulation mechanisms or any fiscal measures, such as reimbursements for or exemptions from specific taxes. Beneficiaries may e.g. receive discounted VAT rates or other taxes.

## 10.2 An assessment of EU policies and support schemes for RES-E

Support policies have led to a significant expansion of RE in the EU and worldwide. From 2005 through 2015, more than 1,300 RE support measures of different kinds (such as financial and regulatory) were put in place by the EU Member States.

Policy makers generally focused on the RES-E sector, designing mainly financial incentives based on feed-in systems. The predominantly adopted concept to design support levels and schemes appeared to be based on the cost of energy. (Banja et al., 2017)

The development of NREAPs and their progress are monitored in the EU's NREAP progress data portal.[10] Every second year, each MS must publish a progress report.

Table 1 presents the support schemes for RESs which were adopted by the MSs during the early years after the RED ("•" indicates the scheme which is primarily used). The table confirms that many countries have implemented a mix of different support schemes, where the Feed-in Tariff (FIT) is the most widely used instrument, followed by Premiums, tenders and quota systems.

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[10] https://ec.europa.eu/jrc/en/scientific-tool/nreap-data-portal

Table 1: RES-E support schemes adopted by the EU-28 during the first years after the RED

| | Feed-In Tariff | Premium | Tender | Quota | Subsidy | Net metering | Tax benefit | Loan |
|---|---|---|---|---|---|---|---|---|
| Austria | ● | | | | ○ | | | |
| Belgium | | | | ● | ○ | | | |
| Bulgaria | ● | | | | | | | |
| Croatia | ○ | ● | ○ | | | | | |
| Cyprus | ○ | | | | ● | ○ | | |
| Czech Republic | ● | ○ | | | ○ | | | |
| Denmark | | ● | ○ | | | ○ | | ○ |
| Estonia | | ● | | | | | | |
| Finland | | ● | | | ○ | | | |
| France | ○ | ● | ○ | | | | ○ | |
| Germany | ○ | ● | ○ | | ○ | | | ○ |
| Greece | ○ | ● | ○ | | ○ | ○ | ○ | |
| Hungary | ○ | ○ | ○ | | ○ | ○ | | ○ |
| Ireland | ● | | | | | | | |
| Italy | ○ | ○ | ○ | | | ○ | ○ | |
| Latvia | ● | | | | | ○ | | |
| Lithuania | | ● | ○ | | ○ | ○ | ○ | ○ |
| Luxembourg | ● | ○ | | | ○ | | ○ | |
| Malta | ● | | | | ○ | | | |
| Netherlands | | ● | ○ | | ○ | ○ | ○ | ○ |
| Poland | ○ | ○ | ● | ○ | | | ○ | ○ |
| Portugal | ● | | | | | | | |
| Romania | | | | ● | ○ | | | |
| Slovakia | ● | | | | ○ | | ○ | |
| Slovenia | | | ● | | ○ | | | ○ |
| Spain | ○ | ○ | ● | | | | | |
| Sweden | | | | ● | ○ | | ○ | |
| United Kingdom | ● | | ○ | ○ | | ○ | | |

## 10.3 Support schemes for Electricity from Renewable Energy Sources adopted by the EU Member States

If not differently specified, the input data to this section is taken from the following sources and not additionally cited:

- The Website *RES Legal - Legal Sources on Renewable Energy*[11] and its sub-pages, and
- The National Renewable Energy Action Plans (NREAPs) (cf. section 9.3.1).

Note: the data reflects the current (2019) situation of RES-E support, however, several countries have adapted their support policies over the course of time. Further information is available in the archives at RES-LEGAL and in Banja et al. (2017).

### 10.3.1 Austria

Refer to section 13.

### 10.3.2 Belgium

Belgium was an early adopter of a quota system and therefore serves as an example for this support mechanism. Despite the small size of the country, RES-E support mechanisms are divided into national (federal) and regional (Brussels, Flanders, Wallonia) competences.

Main support scheme: quota system based on quota obligations. Other support schemes in use: subsidies (RES investement support), net-metering, tax-reductions. In general, all RES-E technologies are eligible for support.

The NREAP refers to and summarizes the regional as well as federal binding laws. In regards to RES support schemes, it specifies benefits and obgligations, and compares the main characteristics between federal and regional responsibilities. It categorizes into support for production and support for investment.

As per the quota system, electricity suppliers must submit certificates ("certificats verts"[12]) which prove the proportion (quota) of RES in the electricity provided by them.

The quota is split into a statutory and continuously increasing portion. A minimum price per certificate is guaranteed by law.

Fundamental differences between the entities are accounting unit (certificates are granted either based on produced energy (MWh) or avoided $CO_2$ emissions), recognition of certificates (across entities), the certificate validity as well as duration of benefit.

**Federal quota system** Responsible for registration, allocation and authenticity of green certificates: Federal Electricity Regulatory Authority of Belgium (CREG)

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[11] `http://www.res-legal.eu`

[12] (french) green certificates

Eligible technologies: offshore wind and hydro power (all others are covered by the regional quota systems).

A certificate is tradable and has a validity of five years. Per generated MWh of RES-E, one certificate is issued. The acquired certificates are then traded with the federal system operator, who is obliged to buy them during a period of 10 years (20 years in case of off-shore wind).

**Brussels Capital Region (BCR) quota system** Issuance and allocation authorityis: Brussels Regulatory Authority (BRUGEL).

Formula for certificate allocation: relation between electricity generated and $CO_2$ saved. Different technologies are differently graded, and quotas are set for each year by BRUGEL. Certificates are valid for 5 years and have a minimum price. Suppliers are fined in case they do not reach their quota.

**Flanders Quota System** Issuance and allocation authority is the Flemish Regulator of the Electricity and Gas market (VREG).

The ruleset for certificate issuance is different to the national scheme; as such, several factors decide about whether a certificate is issued: plant size, year of erection, banding factor. Minimum prices are set by law and electricity suppliers that fail to meet their obligation (i.e. quota) will be fined.

**Wallonia Quota system** Issuance and allocation authority is the Walloon Energy Commission (CWaPE).

Considering a target of 8,000 GWh of RES-E by 2020, 1 certificate per generated MWh from RES is issued, taking into account several additional factors (investment amount, emissions, electricity price).

Eligible technologies: all for one time only (for a period of 10-15 years depending on technology).

Minimum prices of certificates are guaranteed and the grid operators are obliged to buy certificates from electricity producers (otherwise they are fined).

### 10.3.3 Bulgaria

Bulgaria's NREAP describes obligations and incentives for participants of the RES-E market and increases the feed-in priority of RES-E producers (except hydropower plants of over 10 MW installed capacity). It is guaranteed by law that RES-E is purchased (obligation), and purchase agreements are granted up to 25 years. As an additional incentive, access and connection to the grid is also guaranteed to producers as well as reimbursements of the connection cost.

Main instrument to promote RES-E in Bulgaria is the Feed-in Tariff (FIT), for which the legal framework is given by the "Act on Renewable Energy Sources (ERSA)". The tariff rates are set on an annual basis. Applicable technologies for incentives and the FIT are: Photovoltaic (PV) and biomass (indirect use).

### 10.3.4 Croatia

Croatia uses different means of support, allocated through tenders, for which all RES-E technologies are eligible.

The “RES act”, effective 2016, laid out the primarily used premium tariff scheme which replaces the earlier in-use FIT-like tariff system. Other adopted support schemes are loans and FIT. Guidance, rules and conditions are given by a ”Rulebook on Renewable Energy Sources”, which also specifies the tendering process.

The NREAP states that Croatia plans to reach its Renewable targets exclusively through the usage of domestic RESs, and expects 35% of the electricity consumption produced from RESs.

**Feed-in Tariff (FIT)** Plants up to a capacity of 30 kW are eligible to a FIT scheme, allocated as well through public tendering.

**Loans** Dedicated Funds as well as the Croatian Bank for Reconstruction and Development (HBOR) award loans and other means of financial grants without interest, to incentivize RES-E investments. Depending on the source of the grant, the rulebook may be applicable for the conditions.

### 10.3.5 Cyprus

Cyprus’ approach of promoting RES-E is specific to technology, plant capacity audience. Adopted are a (comparably) short-term FIT, a net-metering scheme, as well as and small-scale subsidy programme for PV and biomass installations up to 3kW.

Plant types eligible for support are: PV, wind, biomass, biogas, tidal and Concentrated Solar Power (CSP).

**FIT** The FIT is applicable to wind, solar (PV and CSP), biomass and wave energy. It is foreseen as a support scheme for power plants, however limited to a period of 12 months after launch with the objective of transitioning into the “competitive electricity market” integration.

### 10.3.6 Czech Republic

Czech Republic has suspended its Renewable support schemes (FIT and Premium tariffs) for new plants by end of 2013, with the exception of subsidies for small scale hydro power plants.

### 10.3.7 Denmark

Denmark mainly uses premium tariffs to promote the production of RES-E. Besides that, adopted support schemes are loans (incentives for the construction of wind energy plants) and net-metering. Technologies eligible for support are wind, biogas and biomass, solar, tidal and hydro, up to a capacity of 10 MW.

**Premium tariff** Through the premium tariff, plant operators receive, for each unit of electricity fed into the grid, either a variable/maximum (capped) or a guaranteed bonus on top of the electricity market price.

All technologies are eligible to apply for a premium tariff, however, in case of offshore wind parks, allocation happens through tenders. The duration of support as well as other conditions and rules vary between technologies, plant capacities and their initial commissioning dates.

**Net-Metering** The net-metering support scheme is applicable to all technologies except geo-thermal, and follows specific conditions. In principal, depending on the amount used for their own needs, electricity producers are exempt from paying the Public Service Obligation (PSO) on this amount of electricity produced.

### 10.3.8 Estonia

Estonia has mainly adopted a classic premium tariff scheme to promote RES. Certain conditions may apply, but in general all generation technologies are eligible for this support scheme, which is limited to a maximum period of 12 years from the date of commissioning.

The initial NREAP had planned a FIT based promotion as well as other incentives.

### 10.3.9 Finland

Finland promotes all types of RES for energy generation with financial support system, i.e. subsidies (grants); the "production support scheme" (cf. NREAP) is implemented as a Feed-in Premium (FIP). All support schemes are mutually exclusive and applicable one time per plant.

The NREAP shows an increased focus on biomass (cf. section 12.1.9). It denotes the production support scheme as FIT scheme, however it is actually a premium tariff.

**FIP** Eligible technologies for the premium tariff are wind energy, biogas and biomass, and producers receive a variable tariff for a timespan of maximum 12 years. The support scheme comes with certain conditions towards plants such as capacitiy constraints or co-generation. As to biomass, wood chip and wood fuel plants are the only supported types eligible for a premium tariff.

### 10.3.10 France

France's leading promotion instrument for RES-E since 2017 is a compensation mechanism, put in place through a premium tariff. Until then, FIT was the main support scheme adopted. In general, all technologies are eligible for Renewable support schemes, which are supervised by Commission de régulation de l'énergie (CRE), the French authority for energy regulation. Besides the premium tariff, France has adopted a mix of schemes, including the FIT (still applicable to small-scale installations upon certain rules), tax benefits (income tax credits or Value Added Tax (VAT) reductions), tenders and subsidies.

**Premium tariff "compensation mechanism"** Producers get allocated a premium on top of the market electricity price, for a period of 20 years. The premium tariffs are allocated either via direct contracts with the producers or via public tendering, based on the installation size.

The scheme defines calculation formulas and eligibility criteria for each RES technology.

### 10.3.11 Germany

The landscape of RES-E support in Germany is broad, offering many kinds of schemes. All technologies are eligible to all schemes per default, however restrictions may apply based on capacity, location or materials.

Today, FIP is the main support scheme applied, whereas FIT applies only to small installations up to 100kW. Apart from that, a mix of support instruments including investment subsidies in form loans, or incentives for on-demand capacity (flexibility surcharge and premium).

**Tendering** Selected plants and capacities (wind and PV larger than 750kW and biomass starting at 150 kW) are awarded through public tenders, as well as their level of support.

**Market premium** The premium tariff became the main support scheme for RES-E in 2014 and is either available the classic way (application and assignment) or awarded through tenders. In the first case, the amount includes the legally fixed FIT rate, plus a monthly calculated premium, following a specified formula (market dependent).

### 10.3.12 Greece

With 2017 however it was replaced by a premium tariff system. In adition, subsidies and tax benefits are adopted means for support. Generally, RES-E promotion is technology independent.

**Premium tariff** Greece has implemented a sliding FIP for all RES-E technologies as its main support instrument for RES-E support. Starting at 1 MW (for wind 6 MW) capacity, support is granted exclusively through technology-specific tendering.

**FIT** today only applies to rooftop PV up to 10 kW capacity and selected smaller plant types such as wind (up to 3 MW) or any other technology up to 500 kW ("feed-in premium exemptions").

### 10.3.13 Hungary

A similar development as in Greece can be observed in the Hungarian RES-E landscape of support schemes. The FIT which formed the major instrument until 2017, was replaced by a technology specific FIP, optionally assigned through tenders. From the perspecitve of support, all technologies are covered by at least one scheme. Besides feed-in systems and tendering, subsidy programmes also play a small role.

**FIT** The Feed-in Tariff is applied for installations with capacities between 50 and 500 kW, and which are not subject to tendering.

**Premium tariff** Hungary's FIP system is called "green premium" and applies to all RES-E installations. Plants of capacities between 0.5 and 1 MW do not require tendering, and the tariffs are based on market reference prices. By definition, support is indifferent with regards to conversion technologies.

However, eligibility periods may vary (e.g. they are longer for biomass than for others). Since 2018, the eligibility criteria were further specified and are now subject to a technology and capacity specific cap.

Starting at 1 MW capacity (and all wind plants regardless of capacity), plant operators are obliged to participate in public tendering procedures, through which they get the support granted. The support amount and period are capped.

### 10.3.14 Ireland

A FIT based support scheme called "REFIT" with 2 evolutions ("REFIT 2" and "REFIT 3") were in place between 2010 and 2015, but then abolished. At different stages, either biomass or biogas (or both) were eligible technologies for support. In both cases, eligibility was specific to feedstock and conversion types as well as capacity.

Since the beginning of 2016, no further support for new RES-E installations is in place.

### 10.3.15 Italy

Italy supports all kinds of RES-E technologies, with either a guaranteed minimum purchase price or tax benefits.

**"Ritiro dedicato"** is a purchase agreement under which the producers sell their electricity for a guaranteed minimum price, which are calculated by the energy authorithy, and granted for a period of one year. For wind and solar plants, Italy offers VAT reductions to plant operators. Other available tax benefits are reduced real estate taxes, to which all kinds plants are eligible.

According to the NREAP, Italy used to additionally have a certificate/quota system in place, which was frozen by 2012 however.

### 10.3.16 Latvia

Latvia used to provde a mix of support instruments until 2011, comprising of FIT, quota and tendering mechanisms. However, support for new installations was suspended in 2011 and is planned to be revised after 2019.

Despite the short period of support, Latvia reached a remarkable share of RES-E, 33.5% per 2014, with the 2020 goal being 40%. In the adopted FIT scheme, all RES-E technologies were eligible, except geothermal; the amount of purchase guarantees was capped in terms of full-load hours per year, differing for each technology.

### 10.3.17 Lithuania

In Lithuania, the main promotion is achieved through a sliding FIP tariff scheme. As of date, no new installations receive support, but a new support scheme is scheduled to be introduced by 2019. Apart from that, subsidies e.g. in form of loans are also available, as well as tax benefits (electricity from RE is generally exempt from excise duty). Also, a technology specific cap of support is in place.

**Feed-in Premium** The sliding FIP is applicable to all RES-E technologies expect geothermal, up to a capacity of 10 kW. Above that capacity, tender procedures are used to award premium tariffs, which are valid for a period of 12 years.

**Tenders** are held technology specific and are used to award the FIP.

### 10.3.18 Luxembourg

The main promotion schemes adopted by Luxembourg are tariff based, accompanied by subsidy schemes and tax benefits. Only geothermal energy is excluded from RES-E support.

**FIT and FIP** Support through either a Feed-in Tariff or a Feed-in Premium is available to all technologies, but there are technology specific limitations in terms of capacity. The tariffs are guaranteed for a period of 15 years, but their calculation depends on both the plant's year of first commissioning and its capacity.

**Subsidies** Among different subsidy schemes, technology neutral means are investment grants, aiming to substitute up to 45-65% of cost difference that arise from the use of RES compared to conventional sources.

### 10.3.19 Malta

Malta provides RES-E support for Solar and wind energy only, and the plant type/capacity decides about the support scheme.

**Feed-in Tariffs** are granted exclusively to PV installations up to a capacity of 1 MW, and are guaranteed for a period of 20 years. The tariffs depend on capacity and are amended on a regular basis; an annual cap of the generated volume of electricity supported is defined.

**Tendering** was introduced in 2018 only and is applicable to both PV and wind energy plants. It targets large scale RES-E installationas with a minimum capacity of 1 MW. The tender awards market premiums at a support duration of 20 years.

### 10.3.20 Netherlands

The Netherlands mainly promote RES-E with a FIP tariff. Other support instruments include tax regulation mechanisms and loans. By default, all common technology types are eligible for support, with each support scheme having a different focus.

**Premium tariff** The FIP is laid out in a way that it compensates RES-E plant operators for the delta between the wholesale price of fossil-electricity and renewable electricity. For each technology, an extensive ruleset specifying eligibility requirements, period and amounts is defined. Tariffs are amended on a yearly basis.

**Loans** are granted to any plant technology except biomass/biogas, with reduced interest rates.

**Tendering** was and is applied for off-shore wind parks only, with the objective of increasing the capacity of off-shore wind power plants to 4,500 MW by 2023.

### 10.3.21 Poland

Poland has a tendering scheme in place, which is put in order to award support for any RES-E installation, through FITs or FIP tariffs. Tendering replaced the previously used quota system as the main RES-E support scheme in 2016.

**FIP for unused electricity** applies to Biogas and Hydro plants at capacities between 500 and 1,000 kW. Unused electricity may be sold by the electricity generator to a fixed price. In case this price is lower than the market price of electricity, the gap is filled by the premium tariff. The premium tariff is granted for a period of 15 years.

**FIT for unused electricity** follows a similar purpose and is also applicable to Biogas and Hydro plants, but only for capacities up to 500 kW. Here, a minimum purchase price is guaranteed for unused electricity.

**Technology specific tenders** are held for all RES-E technologies, awarding a guaranteed purchase price for a period of 15 years.

### 10.3.22 Portugal

Purtugal used to provide support for RES-E mainly through a FIT scheme and partly by tax benefits until end of 2012, not excluding any specific RES-E technology. The granted amounts and periods of support depended on the plant technology and capacity. A degression was not applied to the tariffs.

### 10.3.23 Romania

Until 2016, trading green certificates in a quota system built the main RES-E support system in Romania.

**Quota system** All plant technologies were eligible to apply for support, which was granted for a period of 15 years. Since 2017, the quota system is abolished for new installations, but remains in place for existing installations, until their support expire.

**Subsidies** The remaining support framework consists of investment subsidy schemes for own-consumption installations (all technologies) and "less exploited energy sources" (bioenergy, geothermal energy).

### 10.3.24 Slovakia

Slovakia has adopted a mix of FIT (main scheme), subsidies and tax regulation mechanisms to support RES-E plant projects. With a new reformed law effective 2019, support will be granted solely through tenders.

**FIT** Fixed tariffs to compensate market price delta, and additional surcharges are available to plant operators of all technologies, and support is granted for a period of 15 years. Terms comply with the technology types and capacities, based on which support period as well as amount are derived. Tariffs levels are fixed for the overall eligibility period and may be adapted (however only positively) for feedstock dependant plants (i.e. biomass).

**Subsidies** Wind and solar energy plants up to a capacity of 10 kW were eligible to individually designed investment subsidies, subject to available budget.

### 10.3.25 Slovenia

Slovenia primarily uses tendering to support RES-E, awarding subsidies, loans and grants to all types of plants.

**Tendering** has replaced previously adopted FIT and FIP support schemes in 2014, since when it takes place annually. It addresses electricity as well as "highly efficient" CHP plants. The awarded support amount is derived from a stated reference price per technology. Public tenders have technology specific and capacity specific characteristics and their overall support volume is constrained by means of budget caps. Applications must be compliant with NREAP targets in order to be awarded.

### 10.3.26 Spain

Spain had a premium tariff based support scheme in place, phased out by 2013. The tariff system provided technology specific support (amount and duration) under given capacity limits. Starting 2015, regular technology-specific tenders are held.

### 10.3.27 Sweden

The primary concept for RES-E support in Sweden is a quota system with TGCs. Other instruments include subsidies (mainly grants for PV) and tax benefits. In general, the promotion system is technology indifferent.

**Quota system** Quota obligations are calculated based on units of electricity sold, with calculation factors annually set by law. Support is granted for a period of 15 years, and is completely indifferent as to technologies.

### 10.3.28 United Kingdom

The United Kindom has adopted a FIT based system along with a so called Contract for Difference (CfD) system, which comprises of quota obligations with TGCs and tax regulation mechanisms. All technologies are eligible to apply for support in general.

**FIT** The Feed-in Tariff system is available in Great Britain (i.e. England, Scotland and Wales, but not Northern Ireland), for hydro, solar, wind and Biogas plants. Only plants with capacities up to 5 MW are eligible for a FIT, which is guaranteed for a period of 10 (micro-CHP), 25 (PV commissioned before August 2012) or respectively 20 years (any other case).

The tariff amounts depend on both technology and capacity of the selected plant, and are regularly amended. Furthermore, the tariffs are subject to quarterly degression schemes, laid out in a different way as per the plant characteristics.

**Contract for Difference (CfD)** Plants with capacities higher than 5 MW are eligible for support through this scheme.

CfDs are awarded through tenders for a period of 15 years, and essentially represent private law contracts between a RES-E plant operator and the government owned LCCC (Low Carbon Contracts Company). The concept is leaned on market premiums: a “strike price” is contractually defined and if the market price of electricity is lower than this strike price, the plant operator is reimbursed for the the price difference (classic FIP concept). However, this scheme is two-sided, i.e. in case the strike price is lower than the market price, the plant operator is obliged to pay the difference back to the LCCC.

Among all tariff based support schemes in the EU, CfDs are among the most distinctive ones, due to this two-sided dependency.

# 11 The role of biomass for energy in the EU

Previous sections of this work have provided contextual knowledge about the promotion of Electricity from Renewable Energy Sources (RES-E) through various political economic instruments and support schemes in the EU.

While the first part of this thesis treated biomass power plants, in particular their Supply Chains, the upcoming sections will now re-adjust the focus on biomass. Wood will be of main interest throughout the analysis.

## 11.1 Biomass as source of energy

Combustion of wood in order to convert it into thermal energy was and still is a predominant method of utilizing bioenergy by humans. Approximately 40% of the earth population mainly use the energy of firewood for heating and cooking purposes, whereas wood chips are an increasingly used feedstock for “co-firing” in coal power-plants. (Guo et al., 2015)

Advantages of biomass fuels such as being considered as inexhaustible and Renewable Energy Sources (RESs), holding lower carbon-contents than fossil fuels are weight against disadvantages, e.g. low energy densities and hence efficiency grades or even potential conflicts with alternative use. Those disadvantages may lead to biomass not making a significant impact on energy systems in competition with other types of RESs. (Saidur et al., 2011)

With the diverse nature of biomass irrespective of the considered type, the choice of feedstock, pre-processing, its supply chain and the energy conversion method are all important parameters which may effect in a trade-off between economic and technical efficiency.

### 11.1.1 Common feedstock types

Biomass is referred to as the biodegradable portion of material that can be converted into energy. This material, or feedstock, may be products and residues as well as waste, from the forestry and agricultural, but also industrial and household sectors. In the energy context, biomass feedstock is also often referred to as “biofuel”.

The International Energy Agency (IEA) classifies biofuels top-level into

- Solid biofuels
- Liquid biofuels
- Gaseous biofuels (biogas)
- Waste (Industrial and domestic)

which is a typical classification found and commonly used in literature and statistical databases. (IEA, 2018)

The composition and properties of biomass fuels are largely diffuse. Compared to conventional fuels, biomass generally contains a lower amount of carbon and ash content, but more oxygen and hydrogen, as well as volatile components and moisture content. However, those parameters may strongly vary under different combustion properties. Its characteristics and lower heating value make biomass fuels comparable with low-grade coal. (Saidur et al., 2011)

**Solid biofuels** are in essence plants, which are used for direct combustion or as intermediate energy sources: wood (in any form, from direct sourcing or as by-product from agricultural and industrial processes) as well as crops.

**Liquid biofuels** are mainly referred to as biodiesel (bio-oil) and bio-gasoline (bioethanol, bio-methanol), produced from e.g. waste. Liquid biofuels are predominantly used for transport, either pure or blended with conventional fuels. They represent a Renewable Energy Source, as they are fuels from non-fossil, biological origin.

**Gaseous biofuels** such as methane arise from anaerobic digestion and fermentation processes (sewage and waste), or are produced through gasification or pyrolysis of solid biofuels (e.g. syn-gas from wood). Example usage is the substitution of natural gas ("greening of gas").

**Waste** from municipal, agricultural and industrial sources may be used to process in biomass conversion plants, either as direct combustion feedstock for heat and energy production (dedicated or co-firing), or conversion into liquid and gaseous biofuels.

### 11.1.2 The terms "carbon-neutral" and "Renewable Energy Source"

Biomass, in a wider sense, is typically considered as form of Renewable Energy Source (RES) next to wind, solar and geothermal powers; reason of it being that: taking the example of wood or any plants, its inherent energy originates from the sun, and growing biomass takes carbon-dioxide from the atmosphere (carbon storage), while its decomposition or combustion release it back to it.

This idea is well supported by the fact that policies and support mechanisms for RE do cover biomass as well.

Further to the above, the combustion of biomass is also considered as carbon-neutral. The expression "carbon-neutrality" comes from the idea that the amount of $CO_2$ released during the combustion process is equal or less than the amount earlier taken from the atmosphere, i.e. during plant growth. This concept is also referred to as the "carbon-cycle". (Saidur et al., 2011).

While the current work does not aim to challenge this, it shall be mentioned, for the sake of completeness, that scientific as well as non-scientific publications do raise concern and disagreements about this concept. For instance, the EU promoted carbon-neutrality of biomass with the ETS and other national policies, whereas the United States of America (USA) only accepted and adopted such policies starting 2018. This manifests in higher net exports of biomass from the USA to the EU than vice versa. (Beagle and Belmont, 2019)

Ruiz et al. (2015) however suggest that only the cultivation and harvesting processses are considered carbon neutral from the perspective of an energy system. The combustion does lead to process-related emissions.

Consultants of the United States (US) Environmental Protection Agency (EPA) suggest that “carbon neutrality cannot be assumed for all biomass energy a priori” and raise concern about treating all biomass projects equally; the grade of actual “carbon-neutrality” depends on various factors, such as biomass type, conversion and combustion technology, and varies importantly on the time-frame which is being considered in that analysis. [13] (Cornwall, 2016)

Another publication states, in regards to the same topic, that there are conflicting perceptions among different stakeholders interviewed in various EU countries; opposing parties argue about whether burning wood causes any net emissions of $CO_2$ or not, and furthermore about whether it helps emission mitigation to remove carbon-sequestrating trees and in turn burn them, which creates even more carbon. (Peters et al., 2015)

In context of carbon-neutrality, an important aspect is the timeline considered: the amounts of emitted to vs. taken from the atmosphere which build the carbon-cycle. Only then, the term carbon-neutrality can be defined, and furthermore a “payback-period” of carbon derived.

### 11.1.3 Biomass vs. other RESs for electricity generation

Guo et al. (2015) suggest that an essential success criteria of bioenergy over other RESs is the extensive availability of feedstock and an established knowledge, technology base and infrastructure of particularly wood.

Fiorese et al. (2014) argue that the overall life-cycle cost of biomass-to-electricity conversion (including R&D, feedstock, installation and operation) is high and not competitive with conventional sources, unless financial support is in place; or under the constraints that feedstock is cheap, co-generation is viable and the installation is a large-scale plant. According to Banja et al. (2017), financial support schemes for biomass however focus on other key areas than electricity, namely heating and cooling. In this context, Guo et al. (2015) for instance take Renewables support policies for given, when they predict a global increase of bioenergy, meeting a share of not less than 30% of the global energy demand in 2050.

**Availability** A fundamental difference between between biomass and other Renewable Energy Sources is its availability.

Solar, wind, and hydro power (or any other natural resources utilized for RES-E) are intermittent resources, i.e. their availability depends on location as well as short and long term atmospheric conditions.

However, wind and solar power are theoretically infinite sources, and therefore conceptually renewable. In contrast, biomass in its many forms is widely available across the globe (e.g. wood from forests) or arises from human, agricultural and industrial processes (e.g. biodegradable waste). This makes it both a naturally regrowing and artificially growable resource that can be expedited in a projected way.

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[13] `https://blogs.ei.columbia.edu/2011/08/18/is-biomass-really-renewable/`

**Fuel supply and conversion** of RES-E installations is another essential distinction factor of biomass compared to other types of Renewables.

While wind, solar and hydro/tidal power solely depends on intermittent primary resources (wind, sunlight, water) that cannot be substituted in case of non-availability, biomass-to-energy conversion is purely fuel/feedstock oriented; feedstock, that is made available on demand through a supply chain (that may include storage and imports). From this perspective, biomass plants are similar to conventional plants operated with fossil fuels, which also convert the primary fuel into thermal, and furthermore into mechanical and electrical energy.

**Cost** is after all the driving force of success of power plant installations and operations. Biomass is a term for a highly diverse range of materials, whose energy can be exploited. This diversity makes it powerful and weak at the same time.

Due to the feedstock oriented conversion, biomass plants require supply chains that are effective and efficient, both in performance and cost. Refer to Part I of this work for a description of the biomass-to-energy supply chain.

The feedstock itself is a market good, subject of price volatilities. This is an essential difference to other RES, which come “for free”. Also, the diverse nature of biomass fuels creates (theoretically) many opportunities for technical implementations, but at the same time, it increases cost due to many different technologies, which not well proven. Finally, material properties have a significant impact on the efficiency of the feedstock, in terms of energy content but also processing.

To summarize, costs associated with biomass for energy production can be split into (1) cost of supply (covering the whole supply chain), (2) purchasing cost (optionally) and (3) cost of conversion. (Beagle and Belmont, 2019)

**Emissions** should be highlighted in the context of biomass as well. While solar, wind and hydro power plants do not actually emit GHGs or other particular matters during their operation[14], the combustion of biofuels does (energy-related or process emissions).

The main GHG emitted during combustion is carbon-dioxide ($CO_2$), besides methane ($CH_4$), nitrous oxide ($N_2O$) and others. (Saidur et al., 2011) It is suggested that especially firewood is subject to incomplete combustion, if handled incorrectly (oxygen infeed, operating temperature), in which case the emissions increase. (Guo et al., 2015)

In addition to process-related emissions, a supply chain stands behind the operation of biomass power generation plants. With its harvesting, preprocessing, storage and transport steps, the supply chain operation must be considered when assessing emissions of bioenergy. Hence, the consideration of the **overall life-cycle emissions** of bioenergy is vital when addressing utilizing biomass with the objective of reducing emissions (on a global and national scale).

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[14] this shall in no way suggest that the operation or commission of those plants does not entail ecological implications

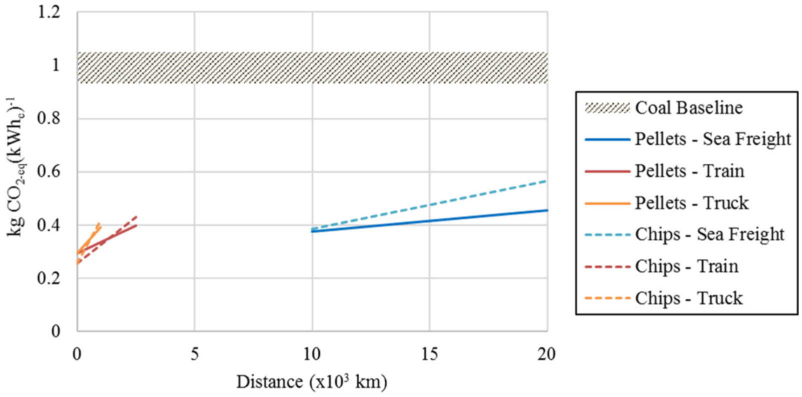

Figure 2: Life cycle emissions per produced kWh electricity in wood chips and pellets fired power plant (source: Beagle and Belmont (2019)[Figure 3])

Beagle and Belmont (2019) conduct a life-cycle assessment of biomass utilization in power plants, in order to analyse emissions. They conclude that for different feedstock types (wood chips and pellets), the emissions of $CO_2$ per generated kWh of electricity are lower than from coal (cf. Figure 2). They suggest that dedicated biomass power plants as analysed in their study could reduce life-cycle emissions by a range of 54-62% in the EU, compared to coal, depending on transportation means and distance.

The above listed constraints make it evident that assessing the realisable potentials of biomass for energy purposes, in particular electricity, is not a trivial task. Numerous publications exist, with commonalities but also large discrepancies. The upcoming sections give further insight into potential assessments in Europe, and also present results.

## 11.2 The use of wood for energy

The combustion of wood is a common way of utilizing the energy contents of biomass for e.g. heating or further conversion purposes. Direct combustion of firewood, when considering a multitude of factors such as harvesting, pre-processing or the overall supply chain, is still the most efficient method of utilizing the energy content stored in biomass, even though the handling of firewood is challenging due to its bulky nature. The latter makes firewood a less applicable feedstock than wood-chips for automated heating systems, where a controlled feed-in in quantity and quality is required for an efficient outcome. Typical units reach combustion efficiencies between 80 and 85% according to Food and Agriculture Organization of the United Nations (FAO). The overall unit efficiency (heat medium and furthermore electricity) is however significantly lower, in the range of 30% (electricity only) or 60% (CHP). (Guo et al., 2015)

Typical classifications of woody biomass, throughout the literature, are

- forest products (stemwood and primary production of roundwood),
- primary forest residues (residues from forest management) and
- secondary forest residues (by-products of industries such as wood chips, pellets or saw dust).

(Ruiz et al., 2015)

**Alternative use** Using wood for energy purposes, in particular wood from forests, creates a major challenge for forests in Europe. Ferranti (2014) discuss those challenges and implications of engaging in an energy future that accounts high importance to forest wood. The uncertainties in quantitative and qualitative potential of biomass are alone an indicator that forest wood is a resource strongly affected by a number of constraints, social, environmental and economic, and that in general the context of energy, electricity and forest wood is a complex topic.

Scientific and non-scientific publications cover a large number of studies about sustainable potential of wood for energy applications as well as sustainability criteria and constraints. This section aims to provide different angles on barriers and potentials of woody biomass for energy in Europe.

### 11.2.1 Processed wood fuel

**Firewood** is regarded as an established feedstock for combustion. Its global consumption, along with charcoal, has remained more or less constant, according to Guo et al. (2015). However, intermediate wood fuels may be necessary to optimize the combustion process and feedstock infeed of large combustion units as they are required for power plants. Advantages of the below mentioned fuels is easier handling and storage, and more efficient drying in order to reach higher homogeneity efficiency grades. Torrefaction is a commonly applied pre-processing technique, as it enhances different handling related properties of biomass such as the grindability, but also combustion related properties (e.g. carbon, hydrogen, moisture content). (Nunes et al., 2014)

**Wood chips and pellets** To overcome the disadvantaged handling of firewood, wood chips have been increasingly utilised as feedstock for co-firing in coal plants. It is expected that electricity generated through combustion of or co-firing with wood chips will double from 2010 to 2020 (Guo et al., 2015). Wood pellets bring similar advantages as wood chips, but their production is more costly. This limits their usage primarily to residential heating in developed countries.

**Charcoal and Syn-gas** A higher price is also hindering charcoal from being increasingly used for electricity; also due to the fact that emissions are higher compared to wood. They appear to be utilized in processes where higher temperatures are required than wood combustion can deliver. Gasification (the process of generating syn-gas) has little relevance as it is not considered cost-competitive and hence not practised in electricity context.

### 11.2.2 Biomass co-firing

Co-firing is the concept of using simultaneously using two or more different fuels in the same combustion unit, with the objective of reducing fuel cost or GHG emissions in existing plants. (Saidur et al., 2011)

Typical applications use wood (e.g. chips, pellets) as co-firing fuel in coal plants, with mixtures of 15-30 vol% wood. One of the technical challenges is the composition of ash arising from wood combustion, which may lead to boiler slagging and fouling, or deposits and corrosion issues. This imposes an upper limit of 30 vol% wood on co-firing mixtures, Guo et al. (2015) suggest. For similar reasons, Saidur et al. (2011) claim that the share of biomass in co-firing units is usually limited to approximately 20%, depending on feedstock type and combustion temperature.

A study carried out by Liu (2019) suggests that, under consideration of economic restrictions related to biomass availability, the optimal plant size of co-firing plants to remain economically vital is on average 12 MW. The study is limited to existing coal power plants in the USA that are suitable for co-firing with biomass, but the authors demonstrate a strong interrelation between biomass availability and cost in varying transportation distance and plant size scenarios.

Generally, a trend was observed in publications about coal/biomass co-firing, particularly from the USA, potentially due to new policies adopted in 2018, promoting biomass.

**Emissions** There is no absolute consent in the literature as to whether the replacement of fossil (e.g. coal) fuels with biomass, or co-firing, actually results in GHG emissions reduction, as Beagle and Belmont (2019) show. Possible reasons are, in-line with other analyses in regards to biomass, uncertainties and the scope of examination (full life cycle vs. process) as well as assumptions such as the carbon-neutrality of biomass. This manifests in a large variation of results, with publications claiming GHG reductions from biomass plants of up to 85% compared to coal, and other studies suggest that utilizing biomass for electricity generation emits more $CO_2$ than coal.

Beagle and Belmont (2019) compare emissions per unit of produced electricity between coal, dedicated biomass power plants and coal power plants, co-fired with a 20% share of biomass. The consider two types of feedstock (wood chips and pellets) and three transportation means, and show the emissions per kWh electricity over distance of transported biomass feedstock. Results are shown in Figure 2 (dedicated biomass plant) and Figure 3 (co-firing plant), with a comparison of results shown in Figure 4. The results a linear relation between transportation distance/type and emissions, and suggests that even through co-firing of biomass with a share as high as only 20%vol, lower emissions of $CO_2$ (reduction of 12%) can be reached. (Beagle and Belmont, 2019)

### 11.2.3 Non-technical barriers

Notwithstanding that the study presented by Peters et al. (2015) may not be representative for all MSs, it does give interesting insights into the challenges, which the energy wood production may face. The authors interviewed different stakeholders from five EU countries for their opinions, in order to identify potential barriers for the expansion of energy wood production.

One of the major problems seen is the **conflict between material and energy use**, in particular for the round-wood production, causing damage to

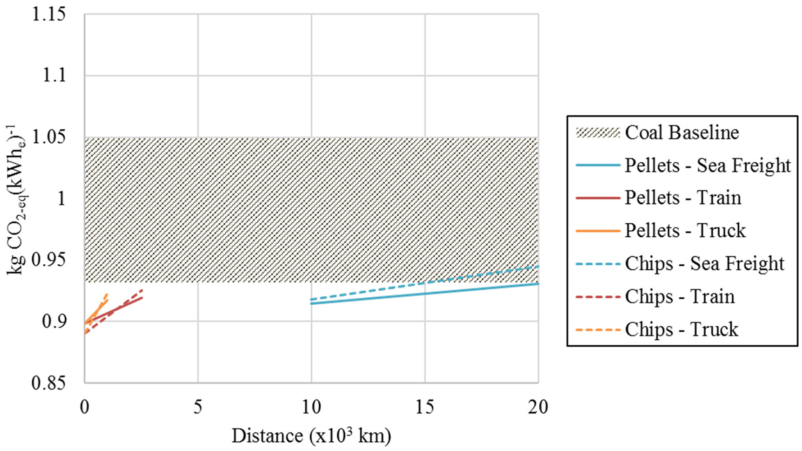

Figure 3: Life cycle emissions per produced kWh electricity in coal power plant co-fired with 20% biomass (source: Beagle and Belmont (2019)[Figure 4])

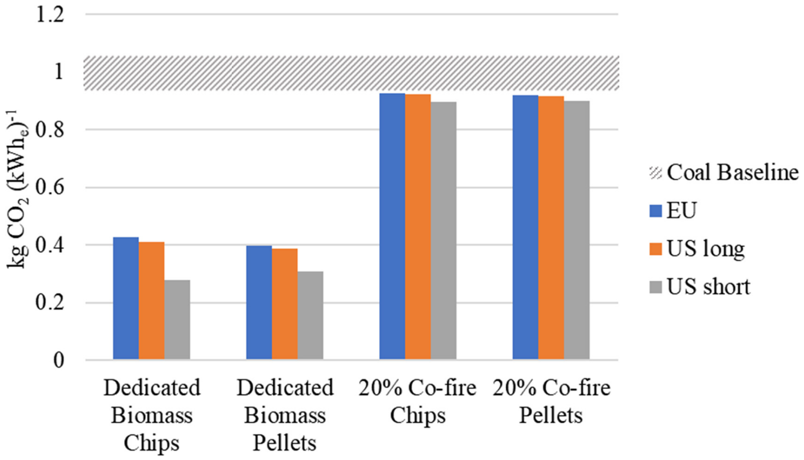

Figure 4: Life cycle emissions per produced kWh electricity in dedicated biomass and co-fired coal plants (source: Beagle and Belmont (2019)[Figure 5])

the forests' structure and biodiversity; and being also seen as worse alternative compared to high quality wood production.

In terms of **resource competition**, stakeholders are particularly concerned about fights between industries and rather see energy wood at the very end of the wood value chain (which basically means, wood ends up as energy wood only if it cannot be used for "higher purposes"). Nevertheless at the same time, producing energy could potentially create opportunities for forest owners or even generate welfare in rural areas.

An important finding is the opinion that **traditional wood industries shall be preferred** by political support, rather than the energy sector; reason being the perception that wood industries yield a much higher value to society than the energy sector, securing jobs and welfare.

The study reveals numerous other aspects that were of concern for the interviewees. Generally, it seems that **conservation and biodiversity** as well as **sustainable forest management** are of high importance. Furthermore, the **intangible value of natural forests for society** was emphasized by numerous stakeholders, representing another barrier to exploit forests for the sake of energy.

The results of this study suggest that there is a common leaning towards resistance against energy usage from different stakeholders of the forestry sector; the presented trade-offs and obstacles outweigh synergies and promoting factors. (Peters et al., 2015)

Sustainability and land use, especially in case of the **competition between food/material vs. energy use** of crops, are also identified as potential areas of conflict in a study by Fiorese et al. (2014). The authors furthermore suggest that **high R&D cost** of biomass technology advancement as well as the scarcity and geographical distribution are substantial barriers to diffusing electricity generation from biomass.

Ferranti (2014) presents an extensive report about energy wood in Europe, addressing not only potentials, but challenges; the main concerns are, again, biodiversity and sustainable use of forest resources. The author provides analysis around environmental implications, conflicts as well as guidance to policy-makers. The report is very focused on the forests themselves and aims to identify trade-offs and synergies among stakeholders associated with the sourcing of energy wood, following similar approach as Fiorese et al. (2014).

Bertrand et al. (2014) briefly mention concerns about the increased use of biomass as energy source. While they accept sustainability concerns such as the impact on fodder, land use and biodiversity, the authors suggest that especially for woody biomass, those externalities are greatly reduced, as wood is not used as fodder; they furthermore suggest that biomass feedstock for energy utilisation shall largely come from residues (forestry and agricultural).

Finally, **forest protection and coservation** laws or harvesting constraints, imposed by private forest owners, may as well have largely negative effects on the overall wood supply potential from forests. (Verkerk et al., 2011)

### 11.2.4 Forest resource assessment

Forests cover a significant part of the earth's surface (more than 30%) and and the global forest area is considered one of the largest carbon sinks. Estimates suggest that the world's forests contain more carbon than the the entire atmosphere. (FAO, 2010)

While it is well acknowledged that forests are more than material and carbon stocks, as they represent diverse ecosystems, the carbon stock is observed to be *the* tangible aspect in scientific and political discussions.

**The Food and Agriculture Organization of the United Nations (FAO)** plays an important role in collecting forest resources, monitoring global forests since 1946. FAO's Forest Resources Assessment (FRA) is regularly published, with continuously dynamic scope.

The most recent dates to 2015. It provides a reporting framework to participating countries in order to collect metrics, such as the area of forest, volume of standing wood, forest biomass (above-ground (ag), below-ground (bg) or sous-terrain, dead-wood) as well as the carbon stock stored by those forests. Furthermore, the FRA reports provide indicators and trends in regards to each of those metrics, and emphasize the less tangible topics such biodiversity, economic and social benefits of forests, and most importantly sustainable forest management. (FAO, 2015)

FAO suggests that since 1990, European forests show an increase in total biomass stock, while the world wide overall trend is a declining. Table 2 contains data extracted from FAO (2015), supporting this statement. Some rows are bold, in order to highlight summed up items and/or to facilitate the comparison with other data sources. It shall be noted that "Europe" refers to the European continental area, rather than the EU territory, and without the Russian Federation. This area accounts to approximately 5% of the global forest area.

Note: The "biomass ECF" describes the biomass expansion and conversion factor: above-ground biomass in t divided by growing stock in $m^3$. The root-shoot-ratio is defined as below-ground biomass divided by above-ground biomass and the dead-live-ratio is defined as dead biomass divided by living biomass.

**State of Europe's Forests (SoEF)** reports are focused on sustainable forest management in Europe, including all EU Member States. They date back to 2003, with the most recent report being published in 2015. SoEF provides guidelines, criteria and indicators in order to promote sustainable management of forests. Furthermore, it is a source of quantitative data for those parameters. (FOREST EUROPE, 2015)

Table 3 contains the extent of forest area, Forest Available for Wood Supply (FAWS), growing stock as well as the carbon stock in Europe and EU-28, as determined by FOREST EUROPE (2015). Forest area, growing stock and carbon stock may be directly compared with Table 2, however, the set of countries used for "Europe" is different. Data values presented in SoEF are slightly deviating from FAO's FRA data in both quantity and quality. However, both organisations observe similar trends, which is shown in Table 4. The advantage of SoEF over FRA is the specific treatment of EU-28, which is more

Table 2: Forest assessment in Europe (without Russian Federation), data from FAO (2015)

| | **1990** | **2000** | **2010** | **2015** |
|---|---:|---:|---:|---:|
| World Forest area (Mha) | 4,128.27 | 4,055.60 | 4,015.67 | 3,999.13 |
| **Europe Forest area (Mha)** | **185.32** | **193.03** | **198.44** | **200.55** |
| **Growing stock (M$m^3$)** | **23,294.82** | **27,027.43** | **30,798.79** | **32,736.34** |
| Above ground biomass (Mt) | 14,251.11 | 16,500.16 | 19,017.26 | 20,361.16 |
| Below ground biomass (Mt) | 3,675.85 | 4,253.67 | 4,916.99 | 5,236.02 |
| Dead wood (Mt) | 299.24 | 327.72 | 429.17 | 458.18 |
| **Total biomass (Mt)** | **18,226.20** | **21,081.55** | **24,363.42** | **26,055.36** |
| *Biomass ECF* | *0.61* | *0.61* | *0.62* | *0.62* |
| *Biomass Root-shoot-ratio* | *0.26* | *0.26* | *0.26* | *0.26* |
| *Biomass dead-live-ratio* | *0.02* | *0.02* | *0.02* | *0.02* |
| Carbon in ag-biomass (Mt) | 6,961.44 | 8,066.45 | 9,292.08 | 9,936.54 |
| Carbon in bg-biomass (Mt) | 1,797.36 | 2,081.80 | 2,393.27 | 2,550.77 |
| Carbon in dead wood (Mt) | 132.95 | 150.13 | 192.44 | 205.09 |
| Carbon in litter (Mt) | 1,763.62 | 1,799.32 | 1,831.14 | 1,859.26 |
| Carbon in soil (Mt) | 10,997.28 | 11,274.27 | 11,542.41 | 11,702.19 |
| **Total carbon/forests (Mt)** | **21,652.65** | **23,371.97** | **25,251.34** | **26,253.85** |

Table 3: Forest area in Europe and EU-28, 2015; from: FOREST EUROPE (2015)[Table 5, 9, 11]

| | Forest area | | FAWS | Growing stock | Carbon stock |
|---|---:|---:|---:|---:|---:|
| | million ha | % of total land | million ha | million ha | million ha |
| Europe | 215.27 | 32.8 | 165.94 | 35,065.00 | 12,541.00 |
| EU-28 | 160.93 | 37.9 | 134.49 | 26,526.00 | 9,826.00 |

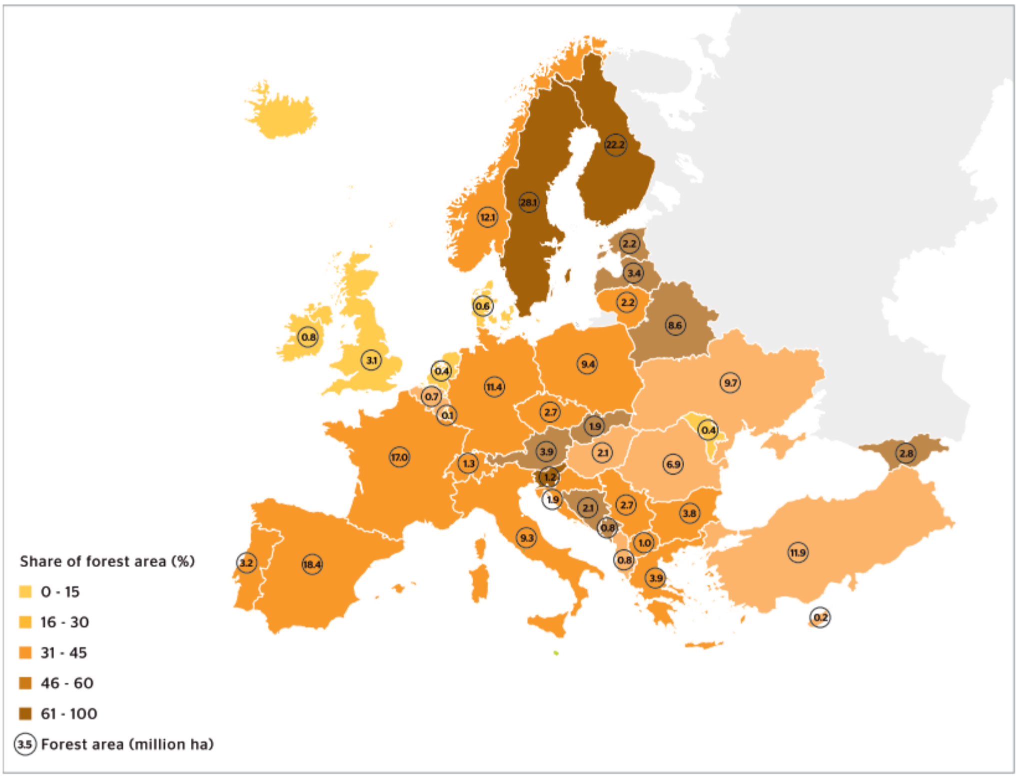

Figure 5: Forest area (million ha) and share (percentage) of land area by country, 2015 (source: FOREST EUROPE (2015)[Figure 19]

relevant for the current work. Figure 5 visualises the forest area quantities in Europe per country.

Despite the evidence that SoEF reports treat different aspects of forest management and sustainability, and that they a valuable source for metrics regarding forestry, those reports do not address the energy utilization of wood in an extensive way. One indicator is mentioned, but neither elaborated nor filled with sufficient data.

### 11.2.5 Wood supply availability data

Over the last decades, the European forest area has grown, while harvesting of wood has decreased. Most European countries use, or are in the process of creating, a national forest inventory in order to assess the wood-biomass supply potential and to project growth. The quality of data varies across countries. (Barreiro et al., 2016)

An essential aspect of estimating the potential supply of wood from forests is, first of all, their division into Forest Available for Wood Supply (FAWS) and Forest Not Available for Wood Supply (FNAWS). This division is typically observed in national forest inventories, and international (e.g. pan-European) forest reports such as SoEF (FOREST EUROPE, 2015) or FRA (FAO, 2010), which also provide guidelines for data reporting. The expression "theoretical potential" is extensively used in scientific literature and white papers, e.g. in potential assessments (cf. section 11.3).

Table 4: Forest area, growing stock and carbon stock in Europe and EU-28, Trends 1990-2015; from: FOREST EUROPE (2015)[Tables 7, 9, 11]

| | | 1990 | 2000 | 2010 | 2015 |
|---|---|---|---|---|---|
| Europe | Forest Area (million ha) | 197.77 | 206.15 | 212.61 | 215.27 |
| | Growing stock (million $m^3$) | 24,999.00 | 28,952.00 | 33,039.00 | 35,065.00 |
| | Carbon stock (million t) | 8,840.00 | 10,178.00 | 11,691.00 | 12,541.00 |
| EU-28 | Forest Area (million ha) | 147.96 | 154.74 | 159.24 | 160.93 |
| | Growing stock (million $m^3$) | 19,169.00 | 21,956.00 | 24,935.00 | 26,526.00 |
| | Carbon stock (million t) | 6,977.00 | 7,998.00 | 9,128.00 | 9,826.00 |

Similar to the observations stated in section 11.3.2, wood supply data is generally not well comparable between countries. Since the late 1990s there have been intentions to developing precise definitions and rules to harmonise National Forest Inventories and similar data collections. (Vidal et al., 2016)

Alberdi et al. (2016) suggest a lack of harmonisation regarding data acquisition parameters, which they intend to overcome by developing a "reference definition". They emphasize that countries' different interpretations of the terms "availability" or "significant" alone (defined in FRA or SoEF) are the issues that mainly affect the consistency of FAWS data, and their accuracy.

Uncertainties also arise from definitions being not sufficiently concise, allowing overlaps and room for interpretation. This is particularly challenging in regards to restrictions (e.g. legal or topological), which are considered sensitive for technical and economic assessments of supply. Evaluating restrictions such as in profitability is considered vital for supply potential assessments. (Alberdi et al., 2016)

It is clear that spatially explicit information on supply potential is key to efficient utilization and planning of wood for energy purposes. Verkerk et al. (2015) conducted a study based on wood production statistics and developed a model of wood harvesting likeliness in Europe, considering ecological, social and economic location factors. They identified (1) productivity, (2) the composition of tree species and (3) terrain/topological conditions as the driving factors of wood production.

## 11.3 Biomass potential assessments

Biomass, especially wood, is traditionally an established source of energy for different purposes, well known in its characteristics and usage. The local availability is furthermore a relevant factor for decentralized energy production, rural economies development, and consequently regarded as a climate friendly means to ensure energy security, while promoting prosperity and regional societal benefits. (Angelis-Dimakis et al., 2011)

It is expected that bioenergy will provide 30% of the world's demanded energy by 2050. (Guo et al., 2015) The fact that it is being promoted as alternative energy source to fossil fuels made biomass, and in particular wood, subject of numerous studies, examining the potential across the globe. This section gives an overview of publications and their major findings in regards to biomass potentials in the EU. The objective however is not to provide detailed figures on biomass supply potential, as this itself would be scope for dedicated research. It will rather outline important findings of existing potential assessments through literature review, with the goal to provide an understanding of how previous assessments were carried out, which tools and methodologies were primarily employed and what restrictions have been observed.

### 11.3.1 Methods and tools

Screening the literature for biomass supply potential assessments shows that there seems to be a common denominator of approaches: statistical databases and forest inventories, combined with mathematical modelling and a Geographic Information System (GIS). That is as far as the commonalities go; no harmonized methodology for global biomass potential assessments is in place to date, creating a diverse landscape of results.

Angelis-Dimakis et al. (2011) present available tools and methods, which are used to determine RE potentials and their exploitable energy, as well as challenges in their exploitation. In the case of biomass, the authors define different levels of potential:

- theoretical,
- techno-economical and
- sustainable,

the latter two consider constraints imposed by stakeholders or geo-topological conditions. In their analysis, the authors explore different forms of dry biomass, such as wood, energy crops, and residues from the agricultural and industrial sectors.

As to woody biomass, estimates are typically based on national forest inventories as well as forest management plans, in the first instance. GISs and satellite images are then used to create spatial distributions of potential, to support economically viable planning. Similar approaches are also used in the first part (cf. Part I) of this thesis.

The authors suggest that the main challenge of bioenergy exploitation is the **accuracy and optimisation of estimation models** in terms of forest dynamics and any kind of **social and environmental factors** interfering with them. (Angelis-Dimakis et al., 2011)

**Cost** is also an important factor taken into account by potential assessments. The evaluation of harvesting cost is highlighted with aspects such as the piling of product, pre-processing (baling and bunching) at the harvesting site and forwarding to the roadside. (Esteban and Carrasco, 2011)

Rettenmaier et al. (2010) have analysed 28 out of 250 bioenergy potential assessment studies within the *BEE (Biomass Energy Europe)* project. They classify the different chosen approaches as (1) resource-focused, (2) demand-driven, where competitiveness of biomass is compared with that of conventional fossil sources based on the demand, and (3) integrated modelling approaches, in which calculations and correlations between socio-economic, ecological, political and technical aspects are built and considered.

Another distinction Rettenmaier et al. (2010) introduce are the methodologies: the summarize them as (1) pure statistical assessments based on data and assumptions, (2) spatial-explicit assessments (e.g. in conjunction with integrated models and GISs), and (3) assessments based on cost-and-supply analysis.

### 11.3.2 Inconsistencies and challenges

Bentsen and Felby (2012) reviewed a large number of published bioenergy potential assessments, on global and EU level. In their work, they focus on the European bioenergy potential; they quantitatively and qualitatively analyse and compare results as well as methodologies and scope.

The review shows that all studies apply different methodologies, scope and assumptions, on different geographical areas and granularities. In essence, they show there is no standardized methodology employed by a majority researchers. Furthermore, the ranking/classification of biomass potentials (theoretical, technical, economical, sustainable) is not consistently used, nor are the sustainability criteria.

The authors observe substantial variations not only in the results from different studies, but more importantly in the underlying questions and resources which motivate them. This eventually creates different types of results which are neither transparent nor do they deliver comparable answers. (Bentsen and Felby, 2012) Similar conclusions had been drawn in other publications, such as from Torén et al. (2011).

Esteban and Carrasco (2011) observe this phenomenon as well, although not addressing it in more detail. They suspect however a lack of information on the used methodology as root cause for the divergence; this itself underlines the above mentioned problem that there is no clear approach. The authors conclude that there is a need to harmonize the way assessments are carried out globally.

Furthermore, the chosen size of the spatial units is not consistent among spatial explicit studies in literature; NUTS[15] Level 3 is however a commonly used granularity for pan-European studies or in general studies concerning multiple countries. Pudelko et al. (2013) assert that NUTS-3 is considered an approximate reflection of basic economic activity, making this level of detail an ideal choice for planning distributed energy scenarios.

An attempt to provide this missing rule-set to promote the harmonisation was made by the *BEE (Biomass Energy Europe)* project, publishing two handbooks about this purpose. (Rettenmaier et al., 2010; Torén et al., 2011)

## 11.4 Biomass-to-energy potentials in the EU

Numerous publications about biomass-to-energy potential assessments have been reviewed. (Angelis-Dimakis et al., 2011; Bentsen and Felby, 2012; Elbersen et al., 2012; Ericsson and Nilsson, 2006; Esteban and Carrasco, 2011; Ketzer et al., 2017; Panoutsou et al., 2009; Pudelko et al., 2013; Rettenmaier et al., 2010; Ruiz et al., 2015; Schueler et al., 2013; Torén et al., 2011)

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[15] Nomenclature des Unites Territoriales Statistiques (NUTS) is a European geocode standard

The review confirmed the above mentioned inconsistencies and challenges that arise from different assessments. Also, some are outdated; however, among the analysed sources, some present consolidated results from a high number of other publications. For that reason, quantitative results presented in this section will be limited to those studies. All results are to be understood as **realisable potential** of biomass energy (that is, energy use as a whole, not only electricity generation). Table 5 provides a consolidated comparison between the results, listing the assessed ranges of total potential of biomass energy in EJ per year. Table 6 contains a sectorial breakdown of the same sources.

It shall be noted, that large scale energy potential assessment studies in context of biomass do not specifically address the generation of electricity. Moreover, the magnitude and spatial distribution of the biomass feedstock analyses see the potential as a form of *utilizing* biomass for energy purposes, rather than material or food use. This is an important consideration to be remembered when determining biomass energy potentials: realisable/sustainable represent already strongly reduced theoretical potentials. However, the utilization for electricity generation brings additional constraints, largely from economic nature (marginal cost of a kWh is far above market price).

Table 5: Total Biomass implementation potential (EJ/yr) in EU-27 from different assessments, 2020-2050

| | TOTAL | | | | | |
|---|---|---|---|---|---|---|
| | 2020 | | 2030 | | 2050 | |
| | min. | max. | min. | max. | min. | max. |
| JRC-EU-TIMES | 8.35 | 18.2 | | | 8.17 | 21.1 |
| Bioboost | | 3.75 | | | | |
| BEE | 3 | 16.8 | 4 | 21.6 | 14.1 | 17.9 |
| biomassfutures | | 18 | | 15.7 | | |

### 11.4.1 Potential assessments considered for their results

**The JRC-EU-TIMES model** presented by Ruiz et al. (2015) evaluates future bioenergy potentials for the EU-28 countries under consideration of support policy scenarios. The model considers cost of logistics and import, as well as emission factors and sustainability aspects, for various feedstock types: agricultural (crops and residues), forestry (stem-wood and residues) and waste.

The results from three scenarios (low, reference, high) show total biomass supply potentials of 8.35-18.19 EJ/year by 2020, and 8.17-21.14 EJ/year by 2050. The authors conclude that the forestry sector represents the largest potential for bioenergy, closely followed by agriculture. (Ruiz et al., 2015)

Table 6: Sectorial Biomass implementation potential (EJ/yr) in EU-27 from different assessments, 2020-2050

| | Forestry Sector | | | Agricultural sector | | |
|---|---|---|---|---|---|---|
| | 2020 | 2030 | 2050 | 2020 | 2030 | 2050 |
| JRC-EU-TIMES | 3.8 - 9.1 | | 2.8 - 9.94 | 4 - 8.03 | | 4.88 - 9.65 |
| Bioboost | 1.186 | | | | | |
| BEE | 1.6 - 4.4 | 0.8 - 4.2 | 1.7 - 2.2 | 0.3 - 9.6 | 0.5 - 14.7 | 15.4 - 19.9 |
| biomassfutures | 0.00 | 0.00 | | 0.00 | 0.00 | |

| | Agricultural residues | | | Waste | | |
|---|---|---|---|---|---|---|
| | 2020 | 2030 | 2050 | 2020 | 2030 | 2050 |
| JRC-EU-TIMES | N/A | | | 0.55 - 1.06 | | 0.49 - 1.55 |
| Bioboost | 1.96 | | | 0.605 | | |
| BEE | 1.0 - 3.9 | 1.5 - 4.4 | 0.7 | (covered by agr. Residues) | | |
| biomassfutures | 0.00 | 0.00 | | 0.00 | 0.00 | |

**The BioBoost project** contained a work package presented by Pudelko et al. (2013), in which the potentials of biomass for energy purposes are analysed for the EU-27 and Switzerland on NUTS-3 level. The authors consider only residues and waste from different sectors in their assessment: agricultural (straw and hay) and animal residues, forest residues, industrial and municipal waste as well as roadside vegetation and "natural conservation matter". They conducted a review of literature, analysing potential assessments for different biomass feedstock types in Europe, for periods starting in 1990, including regional studies.

The results do not provide a forecast, but rather consolidate data from different studies, formulating a status quo: the authors conclude that among the assessed feedstock types, straw (1.96 EJ) followed by forestry residues (1.19 EJ) and municipal waste 0.61 EJ) represent the highest potentials for energy purposes. Figure 6 depicts the total biomass potential assessed, and visualizes the regional distribution of a study addressing only residues and waste, but no living biomass (crops, wood). (Pudelko et al., 2013)

**The Biomass Energy Europe (BEE)** project presented by Rettenmaier et al. (2010); Torén et al. (2011) was an initiative to harmonize methods in order to overcome the previously mentioned inconsistencies in biomass potential assessments. The deviations among 55 analysed studies are significant, with differences as high as approximately 15 EJ/year. Like in other studies, the authors see a challenge in comparing different results, due to largely varying reporting frameworks, different layout and interpretation of definitions. The authors also suggest that political frameworks, in particular policies,

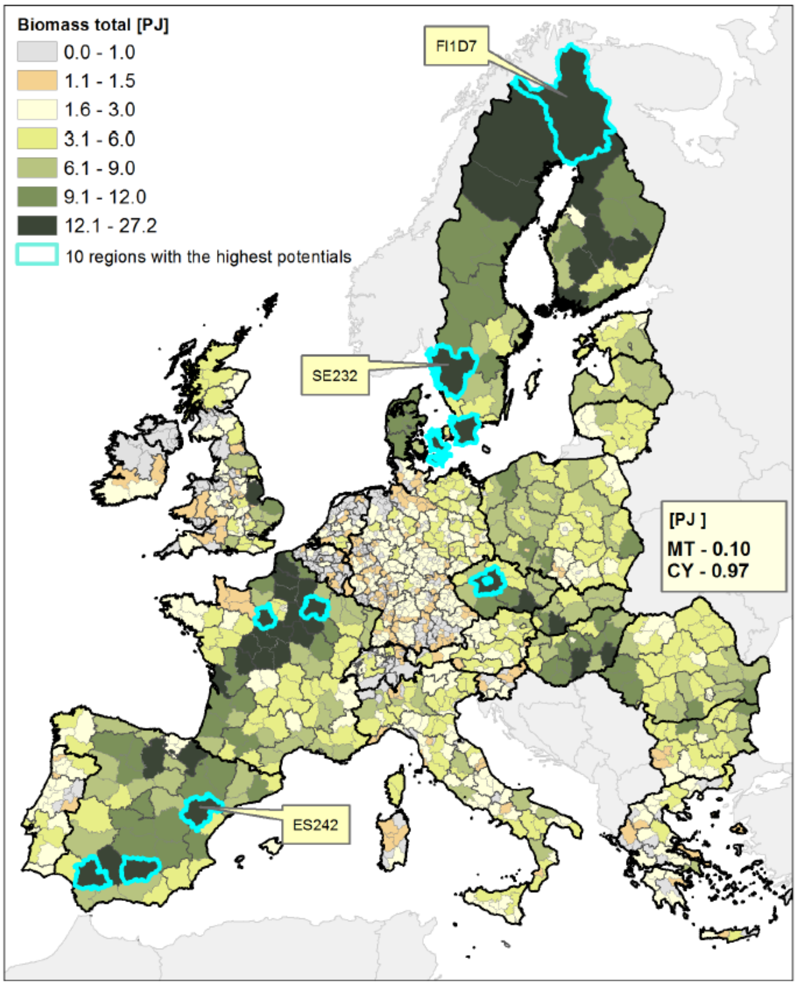

Figure 6: Total Bioenergy potential in PJ on NUTS-3 level, considering residues and waste only (source: BioBoost project (Pudelko et al., 2013)[Fig. 66])

strongly affect scenario assumptions, thus leading to strong deviations in the final (sustainable) implementation potential. The project classifies potential into theoretical, technical and sustainable implementation potential, latter one being a fraction of the economic potential considering social, environmental and political constraints.

Results show an total potential for biomass energy ranging between 8.17 and 21.14 EJ/year from 2020 to 2050, with the major contribution of energy crops. However, the range of energy crops is significantly high, because of potentially preferred alternative use (e.g. food). The report also compares realisable biomass potentials with energy demand in Europe, suggesting that even though the entire demand could not be satisfied with bioenergy, it could contribute with a remarkable share. (Rettenmaier et al., 2010; Torén et al., 2011)

**The biomassfutures.eu** project presented by Elbersen et al. (2012) is widely based on the BEE project (Rettenmaier et al., 2010) data. The report focuses on waste, agricultural residues, different crops, forest products and residues as well as round-wood. The authors estimate the biomass supply potential at date (2010) and also provide forecasts for 2020 and 2030 in a reference and sustainability scenario. In contrast to above mentioned studies however, they also match the potential estimates to biomass feedstock prices, as they consider price a crucial influencing factor in context of material/alternative use. This is particularly pointed out for round-wood, where competing demand leads to high prices, which in turn do not allow economically viable usage in electricity conversion plants. The forecast for the overall biomass supply potential ranges from 14.78 to 17.96 EJ/yr in until 2030, depending on the scenario. They see agricultural residues as the most prosperous feedstock, followed by round-wood production and wastes. (Elbersen et al., 2012)

### 11.4.2 Other assessments considered for their conclusions

Bertrand et al. (2014) do not directly assess the biomass electricity potential, but estimate the demand for biomass based on existing conventional coal plants, if refurbished for biomass or co-firing, and match those estimates with supply figures (from literature, dated 2006-2009). The goal is to evaluate $CO_2$ abatement opportunities as well as switching cost (coal-to-biomass compared with coal-to-gas), in particular with co-firing, and to analyse the relation with the $CO_2$ price. While this approach does not specifically provide quantitative information about the EU biomass-to-electricity potentials, the authors draw interesting conclusions about the relation between biomass and $CO_2$ under the impact of policies and the EU ETS. They suggest that electricity from biomass can be profitable even with high prices for biomass, provided that the carbon price is high enough.

Esteban and Carrasco (2011) use statistics databases for biomass supply potential assessment; they developed mathematical relations to link statistical data with actual conditions, in order to extract the actual biomass-to-energy potential. Aspects considered are the different types of species (trees as well as crops) with their unique properties and lifecycles, as well as soil conditions, slope, erosion risks and the demand for other use. The authors generally consider 20% of the total theoretical potential as unreachable (not collectable with machinery).

### 11.4.3 Biomass-to-energy potential assessments specifically for wood

When reviewing studies assessing wood energy potential, it was observed that the European Forest Information SCENario (EFISCEN) model[16] was a common tool to estimate theoretical and harvesting potential in Europe.

The spread of results in wood related assessments is observed high as well, similar to the above presented studies, given that sustainability (societal, economic and environmental) is an even more sensitive topic with regards to forests.

In order to assure all those aspects are covered , Ferranti (2014) state that it is important for assessment studies to follow a resource-based approach, instead of demand-based (such as employed by Bertrand et al. (2014)). They argue that a resource-based approach tends to overestimate rather than underestimate potentials (which is the case for demand-driven approaches). While this might be inefficient from an economic perspective, it is the more desirable outcome from ecological view.

**The EUwood project** presented by Mantau et al. (2010) is considered the most complete and most comprehensive study at European level (i.e. EU-27), assessing the total potential of forestry based biomass for different uses, including energy. EUwood is powered by the EFISCEN model and National Forest Inventory (NFI) data. The authors used the EFISCEN model for evaluating theoretical potentials, and NFI data to support projections to the future. Out of this theoretical, they extract a “real” potential of material and energy use of wood from European forests, under consideration of defined constraints. Furthermore, they specify three scenarios of mobilisation (low - medium - high), strongly connected to ecological/sustainability constraints and competing use of wood.

Figure 7 visualizes the reduction of theoretical potential to the three mobilisation scenarios, and also depicts the share forest products. The study predicts a total energy potential from forests between 0.8 to 2.7 EJ/year by 2030, depending on the chosen scenario. Those results approximately match the ones from BEE (Rettenmaier et al., 2010), although the upper bound is lower.

In line with previous observations, this is again explained by inconsistent methodologies and assumptions. EUwood provides an extensive analysis on its own methodologies and those of reviewed studies. The authors acknowledge that there are indeed uncertainties in their results and in other studies’ findings. While this uncertainties already have consequences for the assessment of theoretical potentials, they are even more impactful on less tangible criteria, such as ecological and sustainability constraints, and especially for forecasts considering those. Furthermore they acknowledge the quality and quantity of constraints is limited, emphasizing economic constraints.

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[16] `https://www.efi.int/knowledge/models/efiscen`

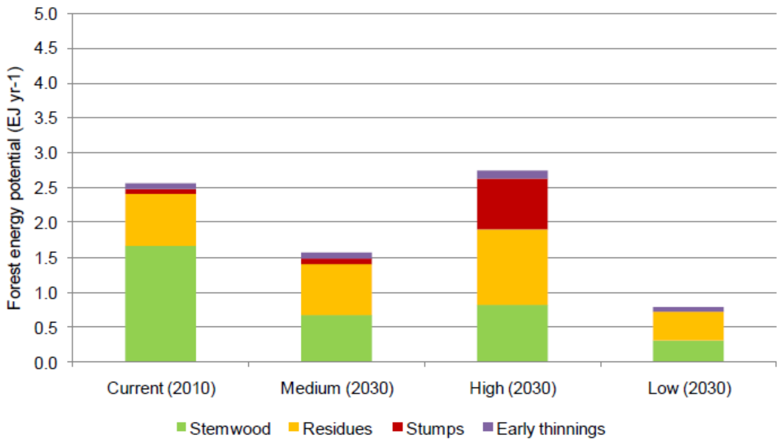

Figure 7: EU-27 energy potentials from forestry biomass in different mobilisation scenarios; source: BEE (Rettenmaier et al., 2010)[Figure 8] derived from EUwood (Mantau et al., 2010)[Figure 4-7]

Their findings and the comparison with other studies let them conclude that mobilisation of wood, for whichever purpose, is strongly influenced by policies and the acceptance of society.

**Another reviewed study** (IINAS et al., 2014) aimed to identify bioenergy potentials in the EU-27 from wood with low biodiversity risks. Their study extends EUwood (Mantau et al., 2010), also making use of the EFISCEN model, with scenarios comparable with EUwood. However, the focus of this study is energy utilization, for electricity, heat and transport, and the GHG emissions of bioenergy.

IINAS et al. (2014) suggest that the share of woody bioenergy in electricity generation will remain constant at approximately 5% (cf. Figure 8) in the "reference" (REF) and "GHG" scenarios until 2030 (while overall electricity generation increases). In turn, the "sustainability" (SUS) scenario only foresees a negligible contribution of wood to the electricity generation. In a wider sense, Figure 9 depicts the share of bioenergy in the EU-27 primary energy supply.

**While above presented studies** consider forest products as well as residues for their assessments, Moiseyev et al. (2011) suggest that forest residues alone are the cheapest type of woody biomass, which makes them the main contributor to bioenergy from wood in their projections. Forest products are considered too expensive to be competitive, and would only play a subordinate role. They assess energy potentials in context of the IPCC scenarios, and primarily drive their analyses based on wood prices rather than on feedstock classification. The authors suggest that the break-even price of energy generation from wood from forest products is lower than the market price for competing use (a similar observation was made by Elbersen et al. (2012)), consequently reducing its potential contribution to energy systems. They also examine interdependencies of wood industries and energy industry, and the impacts of wood energy utilization and energy price on the same.

Figure 8: Forecasted electricity generation and share of Renewables in the EU-27 from 2020 to 2030 in different scenarios; source: IINAS et al. (2014)[Fig. 11]

Figure 9: Forecasted primary energy supply and share of Renewables in the EU-27 from 2020 to 2030 in different scenarios; source: IINAS et al. (2014)[Fig. 15]

Verkerk et al. (2011) suggest that the EU-27 forest area holds an amount of 744 million $m^3$ of woody biomass in 2010 (realisable potential for both material and energy utilization), and project 623-895 million $m^3$ per year for 2030. They base their estimates on the EFISCEN model; the results are somewhat similar to the ones from EUwood (Mantau et al., 2010).

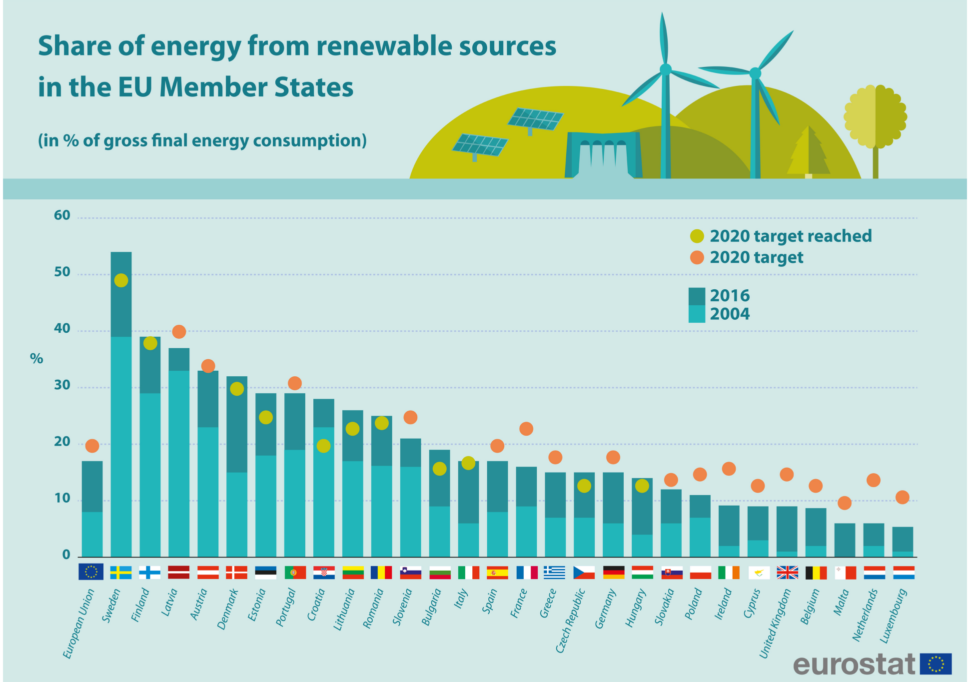

Figure 10: Share of energy from renewable sources in the EU Member States in % of gross final energy consumption 2016 (from EUROSTAT)

## 12 The development of biomass as a renewable source of energy and electricity in the EU

Renewable support policy frameworks under the Renewable Energy Directive (RED) have evidently resulted in a significant gain of Renewable Energy. The share of Renewables in total electricity consumption has rised from 14% (2005) to almost 30% in 2016. With regards to final energy consumption, 2016 data (latest available by EUROSTAT) shows that the share of RES has more than doubled between 2004 and 2016, reaching approximately 17% of gross final energy consumption (target 20%, refer to Figure 10).

The main objective of this section is to provide an overview of RE actions in the EU over the past decades. This will be achieved by presenting planned support mechanisms and energy statistics, in order to draw a connection between evidence of implementation and the aforementioned targets and policies. The primary focus will be biomass, with a particular accent on electricity generation from biomass.

First, the biomass-to-electricity related NREAP actions are listed for each Member State of the EU-28. Second, statistical data about energy in the EU (production and consumption) is presented, in order to show the promotion of RES for the climate and energy targets. A particular focus area will be again electricity from biomass.

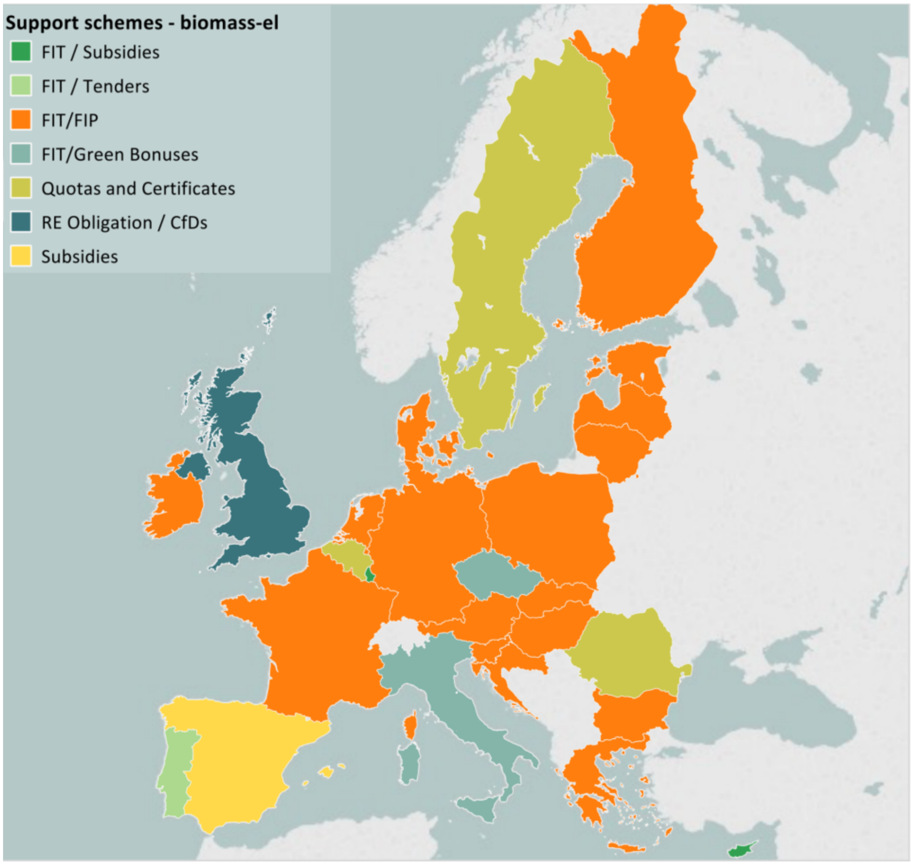

Figure 11: Map showing the used support schemes for biomass electricity (source: (Banja et al., 2017)[Fig. 18])

## 12.1 National action plans, policies and support mechanisms for electricity from biomass

Evidence is shown that policy frameworks have strongly promoted bioenergy worldwide, but especially in the EU. Renewable Energy Policy Network (2018) states that efforts driven by the Renewable Energy Directive (RED) have made the EU leading with regards to electricity from biomass. Fiorese et al. (2014) claim that biomass electricity cannot compete with conventional energy sources (fossil); they rate the probability for that to be the case until 2030 with 21%, unless climate policies including financial incentives are installed. This would, in their opinion, raise the probability to 54%. Comparing the target areas of RE policies shows that EU policies have a stronger focus on biomass electricity, whereas the non-EU policy-makers concentrate more on biofuels.

According to Banja et al. (2017) however, support schemes for biomass are focusing less on the electricity sector than on heating, cooling, grids and infrastructure. Despite the fact that bioenergy still appears with more relevance for heating than electricity (with regards to final energy consumption), global trends suggest that the contribution of bioenergy to the electricity sector has grown faster than others. (Renewable Energy Policy Network, 2018)

This section provides a closer look on biomass promotion strategies imple-

Table 7: Estimation of total contribution to electricity expected from Biomass in 2020, to meet the binding 2020 targets and the indicative interim trajectory for the shares of energy from renewable resources (source: NREAP database)

| **Country** | **Installed capacity [MW]** | | | **Gross generation [GWh]** | | |
|---|---|---|---|---|---|---|
| | **Biomass** | **Total** | **Share** | **Biomass** | **Total** | **Share** |
| Austria | 1,281 | 13,179 | 9.72% | 5,147 | 52,377 | 9.83% |
| Belgium | 2,452 | 8,255 | 29.70% | 11,039 | 23,121 | 47.74% |
| Bulgaria | 158 | 5,189 | 3.04% | 865 | 7,604 | 11.38% |
| Cyprus | N/A | N/A | N/A | N/A | N/A | N/A |
| Czechia | N/A | N/A | N/A | 6,165 | 11,679 | 52.79% |
| Denmark | 2,779 | 6,754 | 41.15% | 8,846 | 20,595 | 42.95% |
| Estonia | N/A | N/A | N/A | N/A | N/A | N/A |
| Finland | 2,920 | 8,540 | 34.19% | 12,910 | 33,420 | 38.63% |
| France | 3,007 | 62,167 | 4.84% | 17,171 | 155,284 | 11.06% |
| Germany | 8,825 | 110,934 | 7.96% | 49,457 | 216,935 | 22.80% |
| Greece | N/A | 13,271 | N/A | N/A | 27,269 | N/A |
| Hungary | 600 | 1,537 | 39.04% | 3,324 | 5,597 | 59.39% |
| Ireland | 153 | 5,111 | 2.99% | 1,006 | 13,909 | 7.23% |
| Italy | 3,820 | 43,823 | 8.72% | 18,780 | 98,885 | 18.99% |
| Latvia | 200 | 2,168 | 9.23% | 1,226 | 5,191 | 23.62% |
| Lithuania | 224 | 1,635 | 13.70% | 1,223 | 2,958 | 41.35% |
| Luxembourg | 59 | 347 | 17.00% | 334 | 780 | 42.82% |
| Malta | N/A | 160 | N/A | N/A | 433 | N/A |
| Netherlands | 2,892 | 14,994 | 19.29% | 16,639 | 50,317 | 33.07% |
| Poland | 2,530 | 10,355 | 24.43% | 14,218 | 32,400 | 43.88% |
| Portugal | 952 | 19,200 | 43.88% | 3,516 | 35,584 | 9.88% |
| Romania | 600 | 12,589 | 4.77% | 2,900 | 31,388 | 9.24% |
| Slovakia | N/A | 2,746 | N/A | N/A | 8,000 | N/A |
| Slovenia | 96 | 1,693 | 5.67% | 676 | 6,126 | 11.03% |
| Spain | 1,587 | 69,844 | 2.27% | 10,017 | 150,030 | 6.68% |
| Sweden | 2,914 | 23,786 | 12.25% | 16,754 | 97,258 | 17.23% |
| United Kingdom | N/A | 38,210 | N/A | N/A | 116,970 | N/A |

mented by the EU-28 and serves as biomass related extension to section 10.3. Biomass for other applications than electricity generation are out of scope and not mentioned. Similar to section 10.3, the data presented below is, unless differently mentioned, taken from the NREAPs as well as RES-LEGAL[17]. Note: the data reflects the current situation of RES-E support, however, several countries have adapted their support policies over the course of time. Further information is available in the archives at RES-LEGAL and in Banja et al. (2017).

Table 7 lists the projected capacities of biomass-to-electricity plants in MW as well as the projected contribution to domestic gross electricity production from biomass per MS, as indicated by the countries themselves. Values shall be understood as estimation of total contribution to electricity expected from biomass in 2020, to meet the binding 2020 targets and the indicative interim trajectory for the shares of energy from renewable resources. The data originates in the NREAP database[18].

#### 12.1.1 Austria

Refer to section 13.2.

#### 12.1.2 Belgium

Biomass as RES is covered by the support schemes implemented in Belgium. Sectors of origin for biomass supply are classified in biomass from forestry, from agriculture and fisheries, as well as from waste.

The NREAP sees opportunities to increase the use of energy crops for electricity generation and suggests a significant surplus in primary energy production from agricultural and fisheries based biomass by 2020. Other sectors appear to have no significant changes compared to 2006 values; for forestry, the plan states that due to optimized efficient use of wood, no significant additional potential is anticipated.

#### 12.1.3 Bulgaria

While primary energy production from biomass is not widely adopted in Bulgaria, experts see potential mainly in CHP plants fired with feedstock from forestry (wood, residues) as well as the agricultural and fishery sectors and waste. Increased usage is forecasted for all those sources, according to the NREAP.

The NREAP does not foresee any specific additional support mechanisms to promote electricity generation from biomass.

#### 12.1.4 Croatia

According to the NREAP, the overall Renewables target is broken down to each RES; as per biomass, the target is to exploit 26 PJ from biomass by 2020, out of which power plants with a total capacity of 85 MW shall be installed.

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[17] http://www.res-legal.eu

[18] https://www.ecn.nl/nreap/data/

No support schemes specifically to promote electricity from biomass are foreseen. It is worth noting that, according to the NREAP, biomass is recognised as important RES for heat production as well as CHP, rather than pure electricity production. It is suggested that Energy crops are not part of the energy strategy of Croatia.

### 12.1.5 Cyprus

According to the NREAP, biomass has a subordinate role for energy production in Cyprus. No significant opportunities are identified for electricity generation and no additional support schemes are planned.

### 12.1.6 Czech Republic

Czech Republic has suspended its Renewable support schemes (FIT and premium tariffs) by end of 2013, with the exception of subsidies for small scale hydro power plants.

### 12.1.7 Denmark

Significant increases and potential are projected for electricity from wood biomass, the NREAP suggests. However, no additional means on top of Renewable support schemes are planned/implemented to specifically promote biomass electricity.

### 12.1.8 Estonia

Biomass plants for electricity generation are only eligible for the premium tariff support scheme, if the plant is a CHP plant. That is, a high potential of energy wood for heat and electricity generation was identified, according to the NREAP.

With the objective of reducing Estonia's dependency on resource imports, a development plan for enhancing the use of biomass and bioenergy was also created.

### 12.1.9 Finland

Finland sees significant potential in energy wood and plans to increase CHP plants fired by wood chips until 2020, according to the NREAP. Experts also state that existing aid policy is not sufficient to promote energy from wood in light of the 2020 targets. Particular measures to overcome those barriers are: financial support for wood chips (in order to increase the price competitiveness compared to other fuels), FIT for small CHP installations and subsidies for small-sized woods (in order to incentivize wood chips production from small-sized woods and increase wood-chips use).

The use of energy crops for production of electricity is not foreseen.

### 12.1.10 France

According to the NREAP, forestry biomass is indeed recognised as significant contributor to meet the 2020 targets (plan to increase the mobilisation of forestry resources to +5.4 Mtoe in 2020), apparently however, not for the electricity sector.

The RES-E promotion strategy for biomass, in particular the premium tariff, considers only electricity generated from household waste. Apart from that, France implemented mainly the FIT scheme, applicable to all technologies.

### 12.1.11 Germany

Germany has no general distinction of technologies when it comes to RES-E support. Plants up to 100 kW capacity are eligible to a FIT, everything beyond is support through Premium tariffs. Biomass plants starting at capacities of 150 kW must be rewarded through a public tendering scheme. Tariffs are valid for a period of 20 years.

**FIT** Biogas plants are only supported in case of CHP. The amount of support is derived from the type of gas. For biomass, no special distinction is made.

**FIP** Also here, biogas is subject to a specific rule set, laying out the conditions under which plants receive support.

### 12.1.12 Greece

The sliding Feed-in Premium is applicable to biomass as to all other RES-E technologies. Amounts are specified per technology and capacity. For biomass and biogas, the support amount is calculated based on “the monthly average of the Marginal Average System Price”[19].

As to biomass for power production, Greece acknowledges its availability in its NREAP but the projections show a very subordinate contribution . However it shall be pointed out that the in place support mechanisms do not seem to discriminate biomass, in fact it shows to be quite indifferent with regards to RES-E technologies.

### 12.1.13 Hungary

As laid out earlier, Hungary’s RES-E support methodology is mosty indifferent with regards to technology types. Similar to Austria, the eligibility period of support is a distinctive factor for biomass incl. Biogas (for non-tendering FIP and FIT) While other RES-E installations receive support for a maximum of 17.3 years, biomass and biogas plants are granted a maximum of 25 years, with the condition of being operational at least for the first 5 years after confirmation of eligibility.

In 2018, the electricity amount for which instalations are supported (non-tendering FIP), were capped at 6,750 kWh (biogas) and 6,900 kWh (biomass) per year repsectively. Furthermore, already operational biomass and biogas plants are, since 2017, eligible to apply for successive tariffs (called “Brown

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[19] http://www.res-legal.eu/search-by-country/greece/single/s/res-e/t/promotion/aid/premium-tariff-feed-in-premium/lastp/139/

Premium", through tendering procedures). That is, plants which are not eligible for "standard" FIT or FIP anymore.

In the NREAP, Hungary regards "reasonable" use of biomass mainly from forestry and agricultural sectors, as well as extensive use of biogas. Bioenergy plants are obliged to fulfil certain efficiency requirements in order to receive support. Furthermore, the feedstock (e.g. wood) must have a declaration of origin. Rather than for large power plants, biomass is preferred and considered mainly for small to medium plants in regional energy systems, to ensure regional synergies and reduce transportation.

### 12.1.14 Ireland

Until end of 2015, Ireland had adopted and implemented a support scheme mainly based on FITs, which had several evolutions, and targeted wind, biomass and hydro-electric plants.

As of 2016, no RES-E support is in place any longer. In 2018, a subsidy programme for PV combined with storage system was introduced, serving as pilot programme for 20 years. New other support schemes are expected to be proposed in 2019.

### 12.1.15 Italy

No biomass specific support mechanisms are considered in Italy.

### 12.1.16 Latvia

As of date, Latvia still has not re-introduced a large scale support scheme for RES-E after it was suspended in 2011. Until then, biomass was treated indifferently with other technologies; support was granted up to 8,000 full-load-hours per annum.

### 12.1.17 Lithuania

No biomass specific support mechanisms are in place; however, the NREAP indicates that by 2020, an annual production volume of 1,223 GWh (installed capacity 224 MW) from biomass is envisaged. Solid biofuels shall contribute with 810 GWh, and biogas with 413 GWh.

### 12.1.18 Luxembourg

Apart from special conditions for biogas plants, under which plant operators can apply for an extension to 20 years eligibility period, no biomass specific support schemes are in place. However, the NREAP did suggest that biomass would, next to wind, represent a "top performer" in the electricity generation. As such, it would receive financial support as high as 33% of the investment cost (valid for power plants and CHP). Eligible plant types are wood chip and pellets combustion plants and gasification.

### 12.1.19 Malta

Biomass is not eligible for RES-E support in Malta.

### 12.1.20 Netherlands

In contrast to other counties, who offer extended support to biomass installations, The Netherlands grant FIPs for 12 years, which is 3 years less than for all other technologies. Biomass and biogas plants are furthermore not eligible for loans.

### 12.1.21 Poland

The NREAP considers biomass next to wind as essential energy source for electricity generation. Biomass is attributed a high potential, and has high importance for reaching the 2020 goals. It is suggested that the primary energy demand for biomass will triple from 2010 to 2020, and solid biomass for CHP reaching an installed capacity of more than 1,200 $MW_{el}$. The main feedstock is wood (chips, pellets) and straw; biomass may be supplied from forestry, agricultural and waste sectors.

### 12.1.22 Portugal

The technology indifferent FIT scheme adopted in Portugal did not foresee any special treatment of biomass plants. As per the NREAP, the contribution of biomass in gross electricity generation was projected to be not significant.

### 12.1.23 Romania

Romania's quota system was closed for new installations by end of 2016. Until then, biomass was treated similar to all other RES-E installations, with regards to support. Since 2017, a national subsidy programme was introduced, which supports only less exploted technologies such as biomass and biogas.

### 12.1.24 Slovakia

Slovak RES-E support schemes, majorly the FIT, did not foresee any specific advantages for biomass. However, the NREAP suggests a high contribution (more than 25% of gross electricity generation) of biomass and biogas in the electricity sector.

### 12.1.25 Slovenia

The NREAP suggests hydro as the main RES-E source to reach the 2020 targets, whereas biomass with approximately 10% of gross generation comes next. It defines technology specific targets, which are then binding conditions for the technology indifferent tendering system.

No biomass favouring RES-E support instrument is in place.

### 12.1.26 Spain

In the current scheme, tenders are hold for one or a group of technologies, but no general restrictions or preferential treatment for biomass are established.

### 12.1.27 Sweden

Sweden's RES-E support through quotas and TGCs is technology-neutral.

### 12.1.28 United Kingdom

The FIT scheme for plants smaller than 5 MW is only available for biogas from anaerobic digestion, whereas CfD (capacities above 5 MW) includes biomass conversion as well. Other than that, no special focus is put on biomass.

## 12.2 EU Energy statistics

If not differently mentioned, the data presented within this section was retrieved from the European Statistical Office (EUROSTAT)[20] databases, tables and publications.

### 12.2.1 Terms and definitions

The following terms are used in the energy statistics databases and throughout this section.

**Gross and net electricity production/generation** represents the total amount of generated electricity through transformation, including own consumption of power plants. After subtracting the consumption of plants, the **net electricity production** remains.

**Gross inland consumption** sums up the overall quantity of consumed energy, for all purposes (generation and transformation of other energy carriers or direct energy use).

**Energy available for final consumption** is the overall quantity of energy that is available to consumers (commercial, industrial, public, private). It includes imports and transformed products, but obviously excludes the energy provided to those transformation processes, as well as exports.

**Gross final consumption** "is defined in the Renewable Energy Directive 2009/28/EC as the energy commodities delivered for energy purposes to industry, transport, households, services (including public services), agriculture, forestry and fisheries, including the consumption of electricity and heat by the energy branch for electricity and heat production and including losses of electricity and heat in distribution and transmission."[21]

For electricity related statistics, an essential consideration is the way how metrics are calculated, i.e. in which context they are expressed. This can lead to significant deviations in interpretation of RES related figures. E.g. the share of RES-E may be expressed in terms of:

- Total installed capacity

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[20] `https://ec.europa.eu/eurostat/web/energy/overview`

[21] `https://ec.europa.eu/eurostat/statistics-explained/index.php/Renewable_energy_statistics`

- Installed capacity in operation
- Gross domestic production
- Net domestic production
- Gross domestic consumption (or gross inland consumption, which includes final electricity consumption)
- Final electricity consumption only (which considers the net domestic production plus imports)

*As an descriptive example, consider:*

- *Domestic net production: 100 TWh, of which RES: 10 TWh*
- *Domestic final consumption: 100 TWh, of which RES: 50 TWh*
- *Import: 40 TWh from RES*
- *Export: 40 TWh from conventional sources*

*According to those figures, the share of RE is 50% in terms of final consumption, but only 10% in terms of domestic production.*

### 12.2.2 Primary energy production and gross inland consumption of RES and biomass

Figure 12 depicts the primary energy production from RESs in the EU-28 countries in terms of quantities (in Mtonne of oil equivalent (toe)) of different RES over time (1990 through 2016). Source data is presented in Table 8. The chart shows an overall strong and steady increase of RESs, with hydro and geothermal power being stable. Significant gains can be observed for wood and solid biofuels, followed by wind and other biofuels.

The gross inland consumption of RESs over time is depicted by Figure 13. It shows a similar distribution and trend as the primary energy production (Figure 12). The breakdown for biomass is visualized in Figure 14 by a stacked area chart (all quantities are stacked upon each other) and can also be found in Table 10. It suggests that solid biofuels have the highest share among biomass resources for energy, followed by liquid biofuels (accumulation of biodiesel, biogasoline and other liquid biofuels), and biogas.

Table 9 expresses the gross inland energy consumption in terms of share (percentage) of RESs. It lists the shares of different RE carriers for all EU-28 Member States in 2016. According to the data, biomass contributes the most to Renewables overall, but the distribution differs from country to country. Significant shares of biomass are seen in the Baltic states, as well as Denmark, Finland and Sweden.

It shall be noted that that the gross inland consumption represents any kind of energy use, not only electricity generation. This explains why the share of biomass is comparable high to electricity generation, as solid biofuels are a predominant energy source for heating, while liquid biofuels are mostly used in the transport sector.

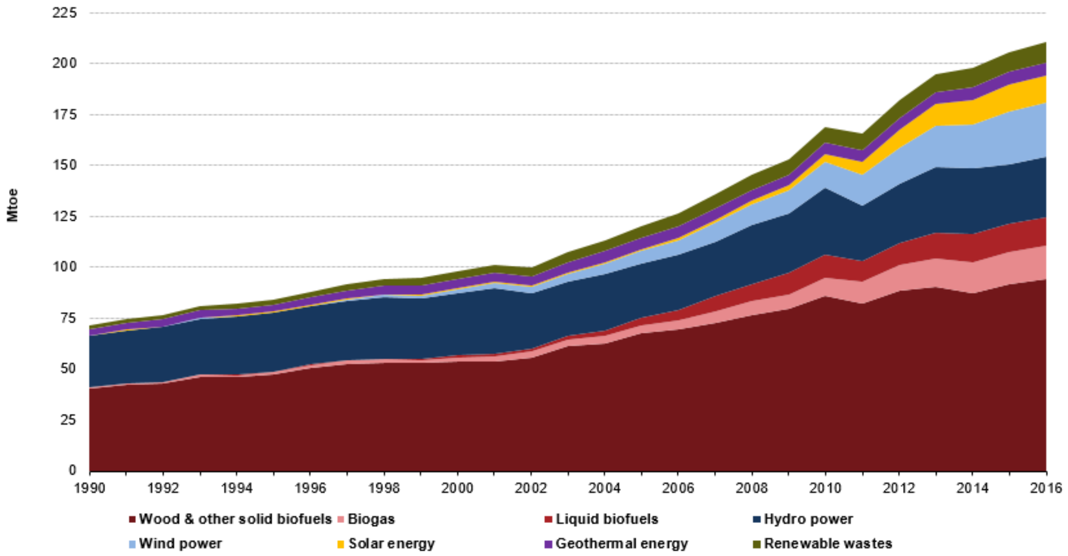

Figure 12: Primary production of energy from renewable sources in Mtoe, EU-28, 1990-2016 (source: Table 8)

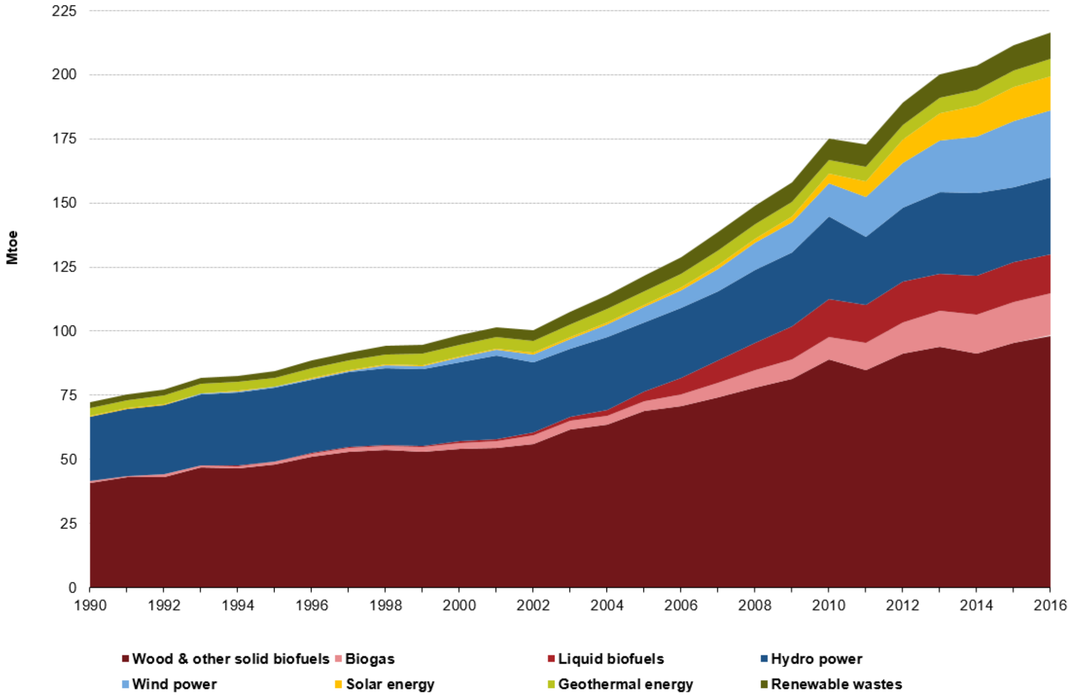

Figure 13: Gross inland consumption of renewables in Mtoe, EU-28, 1990-2016 (source: EUROSTAT, online data code nrg110a)

Table 8: Primary production of energy from renewable sources in Mtoe, EU-28, 1990-2016 (source: EUROSTAT, online data code nrg 110a)

| | **1990** | **1991** | **1992** | **1993** | **1994** | **1995** | **1996** | **1997** | **1998** | **1999** | **2000** | **2001** | **2002** | **2003** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Wood & other solid biofuels** | 40.6 | 42.4 | 42.9 | 46.3 | 46.1 | 47.6 | 50.7 | 52.8 | 53.4 | 52.9 | 53.8 | 53.9 | 55.6 | 61.6 |
| **Biogas** | 0.7 | 0.7 | 0.8 | 0.9 | 1.0 | 1.1 | 1.3 | 1.5 | 1.6 | 1.8 | 2.2 | 2.7 | 3.3 | 3.2 |
| **Liquid biofuels** | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.2 | 0.3 | 0.4 | 0.4 | 0.4 | 0.7 | 0.9 | 1.2 | 1.5 |
| **Hydro power** | 25.0 | 26.0 | 27.1 | 27.7 | 28.6 | 28.5 | 28.5 | 29.0 | 30.0 | 29.9 | 30.7 | 32.6 | 27.4 | 26.6 |
| **Wind power** | 0.1 | 0.1 | 0.1 | 0.2 | 0.3 | 0.3 | 0.4 | 0.6 | 1.0 | 1.2 | 1.9 | 2.3 | 3.1 | 3.8 |
| **Solar energy** | 0.1 | 0.2 | 0.2 | 0.2 | 0.2 | 0.3 | 0.3 | 0.3 | 0.4 | 0.4 | 0.4 | 0.5 | 0.5 | 0.6 |
| **Geothermal energy** | 3.2 | 3.2 | 3.4 | 3.6 | 3.4 | 3.4 | 3.7 | 3.8 | 4.1 | 4.3 | 4.6 | 4.5 | 4.6 | 5.2 |
| **Renewable wastes** | 2.1 | 2.2 | 2.2 | 2.3 | 2.4 | 2.7 | 2.9 | 3.1 | 3.3 | 3.6 | 3.8 | 4.0 | 4.1 | 4.9 |
| | **2004** | **2005** | **2006** | **2007** | **2008** | **2009** | **2010** | **2011** | **2012** | **2013** | **2014** | **2015** | **2016** | |
| **Wood & other solid biofuels** | 62.9 | 67.8 | 69.4 | 72.9 | 76.8 | 79.5 | 86.2 | 82.3 | 88.7 | 90.4 | 87.2 | 91.8 | 94.1 | |
| **Biogas** | 3.6 | 4.1 | 4.5 | 5.8 | 6.7 | 7.5 | 8.7 | 10.6 | 12.4 | 14.1 | 15.1 | 15.9 | 16.6 | |
| **Liquid biofuels** | 2.2 | 3.3 | 5.3 | 7.1 | 8.5 | 10.3 | 11.6 | 10.4 | 11.2 | 12.7 | 14.0 | 13.6 | 13.8 | |
| **Hydro power** | 28.3 | 26.9 | 27.2 | 27.0 | 28.6 | 28.9 | 32.4 | 26.8 | 28.9 | 32.0 | 32.2 | 29.3 | 30.1 | |
| **Wind power** | 5.1 | 6.1 | 7.1 | 9.0 | 10.3 | 11.4 | 12.8 | 15.5 | 17.7 | 20.4 | 21.8 | 26.0 | 26.0 | |
| **Solar energy** | 0.7 | 0.8 | 1.0 | 1.3 | 1.7 | 2.5 | 3.7 | 6.0 | 9.0 | 10.7 | 12.0 | 13.1 | 13.4 | |
| **Geothermal energy** | 5.3 | 5.3 | 5.5 | 5.6 | 5.6 | 5.5 | 5.5 | 5.8 | 5.7 | 5.9 | 6.2 | 6.5 | 6.7 | |
| **Renewable wastes** | 5.3 | 6.0 | 6.5 | 7.4 | 7.4 | 7.7 | 8.1 | 8.4 | 8.7 | 9.0 | 9.3 | 9.6 | 10.0 | |

Table 9: Share (%) of renewables in gross inland energy consumption 2016 (source: EUROSTAT, online data codes nrg 100a, nrg 107a)

| | **TOTAL** | **Biomass** | **Hydro** | **Wind** | **Solar** | **Geo-thermal** |
|---|---|---|---|---|---|---|
| **EU-28** | **13.2** | **8.6** | **1.8** | **1.6** | **0.8** | **0.4** |
| Belgium | 6.8 | 5.4 | 0.1 | 0.8 | 0.5 | 0.0 |
| Bulgaria | 10.7 | 7.2 | 1.9 | 0.7 | 0.8 | 0.2 |
| Czech Republic | 10.3 | 9.3 | 0.4 | 0.1 | 0.5 | 0.0 |
| Denmark | 28.7 | 21.7 | 0.0 | 6.3 | 0.7 | 0.0 |
| Germany | 12.3 | 8.2 | 0.6 | 2.1 | 1.2 | 0.1 |
| Estonia | 15.5 | 14.7 | 0.0 | 0.8 | 0.0 | 0.0 |
| Ireland | 7.5 | 3.4 | 0.4 | 3.6 | 0.1 | 0.0 |
| Greece | 10.9 | 4.8 | 2.0 | 1.8 | 2.2 | 0.0 |
| Spain | 14.3 | 5.6 | 2.6 | 3.4 | 2.6 | 0.0 |
| France | 9.9 | 6.6 | 2.1 | 0.7 | 0.3 | 0.1 |
| Croatia | 23.3 | 15.1 | 6.9 | 1.0 | 0.2 | 0.1 |
| Italy | 16.8 | 8.5 | 2.4 | 1.0 | 1.4 | 3.6 |
| Cyprus | 6.3 | 2.1 | 0.0 | 0.8 | 3.3 | 0.1 |
| Latvia | 37.0 | 31.8 | 5.0 | 0.3 | 0.0 | 0.0 |
| Lithuania | 20.8 | 18.7 | 0.6 | 1.4 | 0.1 | 0.0 |
| Luxembourg | 5.3 | 4.6 | 0.2 | 0.2 | 0.3 | 0.0 |
| Hungary | 11.7 | 10.8 | 0.1 | 0.2 | 0.1 | 0.5 |
| Malta | 3.4 | 1.3 | 0.0 | 0.0 | 2.1 | 0.0 |
| Netherlands | 4.7 | 3.5 | 0.0 | 0.9 | 0.2 | 0.1 |
| Austria | 29.7 | 17.3 | 10.1 | 1.3 | 0.8 | 0.1 |
| Poland | 8.8 | 7.4 | 0.2 | 1.1 | 0.1 | 0.0 |
| Portugal | 24.2 | 12.4 | 5.8 | 4.6 | 0.7 | 0.7 |
| Romania | 19.1 | 12.0 | 4.8 | 1.7 | 0.5 | 0.1 |
| Slovenia | 16.5 | 9.7 | 5.7 | 0.0 | 0.5 | 0.7 |
| Slovakia | 9.5 | 6.9 | 2.3 | 0.0 | 0.3 | 0.1 |
| Finland | 30.7 | 26.0 | 3.9 | 0.8 | 0.0 | 0.0 |
| Sweden | 37.1 | 23.6 | 10.8 | 2.7 | 0.0 | 0.0 |
| United Kingdom | 8.1 | 5.7 | 0.2 | 1.7 | 0.5 | 0.0 |

Table 10: Gross inland consumption of renewables and biomass in ktoe, EU-28, 2008-2016 (source: EUROSTAT, online data code nrg 107a)

| | **2007** | **2009** | **2010** | **2011** | **2012** | **2013** | **2014** | **2015** | **2016** |
|---|---|---|---|---|---|---|---|---|---|
| **Renewable energies** | 149269.60 | 158105.10 | 175206.30 | 172807.40 | 189417.60 | 200423.10 | 203685.70 | 211672.60 | 216617.70 |
| **Share of biomass (%)** | 69 | 69 | 69 | 69 | 68 | 66 | 65 | 65 | 65 |
| **Biomass** | 103019.20 | 109751.60 | 120669.90 | 118647.30 | 128091.90 | 131525.80 | 131453.50 | 136833.30 | 140406.90 |
| Solid biofuels | 78,126.80 | 81,459.60 | 89,016.60 | 84,850.90 | 91,187.60 | 93,761.00 | 91,211.00 | 95,586.50 | 98,280.00 |
| Biogas | 6,677.50 | 7,493.80 | 8,705.70 | 10,611.70 | 12,353.80 | 14,102.30 | 15,119.00 | 15,886.80 | 16,600.10 |
| Mun. waste (renewable) | 7,408.40 | 7,653.60 | 8,110.80 | 8,415.20 | 8,792.80 | 9,204.00 | 9,527.90 | 9,918.50 | 10,320.10 |
| Liquid biofuels | 10,694.20 | 13,028.50 | 14,733.00 | 14,664.30 | 15,621.30 | 14,331.30 | 15,467.00 | 15,306.40 | 15,071.80 |
| Biogasoline | 1,795.70 | 2,267.60 | 2,790.10 | 2,898.40 | 2,867.80 | 2,686.10 | 2,652.60 | 2,704.90 | 2,667.70 |
| Biodiesels | 7,969.20 | 9,562.10 | 10,546.10 | 10,923.70 | 11,869.20 | 10,625.90 | 11,721.40 | 11,412.30 | 11,221.50 |
| Other liquid biofuels | 929.30 | 1,198.90 | 1,396.70 | 842.20 | 884.30 | 1,019.30 | 1,092.90 | 1,190.20 | 1,182.60 |

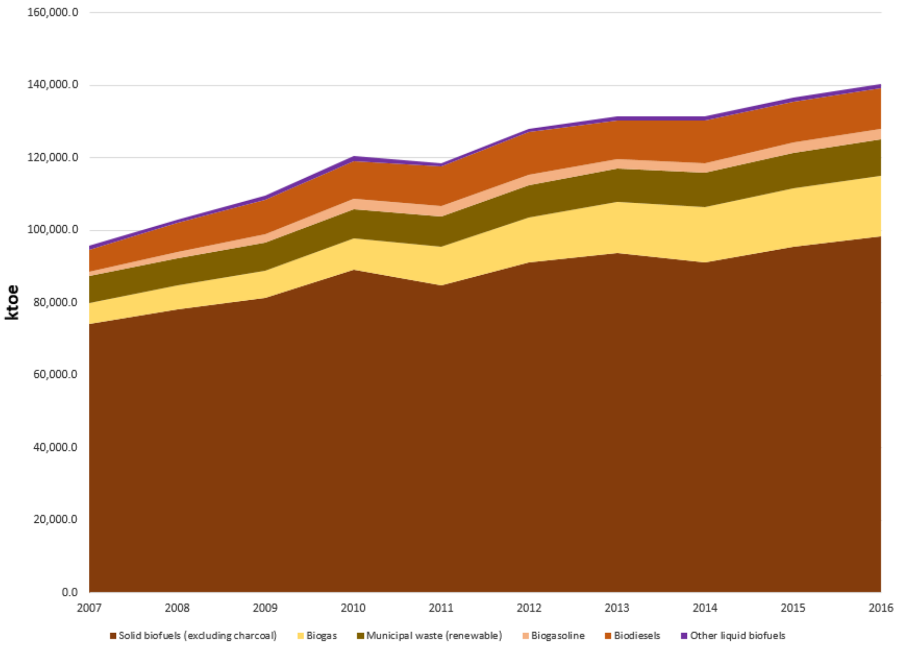

Figure 14: Gross inland consumption of Renewables and biomass in ktoe, EU-28, 2007-2016 (source: Table 10)

### 12.2.3 Electricity demand, production and consumption

The total net generation of electrical energy in 2016 was 3.1 million gigawatt-hours (cf. Figure 15), with almost 49% (cf. Figure 16) generated from combustible fuels.[22]

Note that combustible fuels also include biofuels. The relation between electricity demand, production and consumption, under consideration of imports and exports, is depicted in Figure 17. In this combo chart, the grey areas represent the gross and net production quantities of electricity, while demand and final consumption are indicated by the yellow and black lines respectively. Also, imports and export balances of electrical energy are indicated by red and green bars. All quantities are represented in terawatt-hours, to which the input data to this chart is listed in Table 11. Interestingly, the data suggests that both demand and final consumption of electricity in the EU-28 did not significantly increase over the course of 10 years (whereas the long-term trend (1990-2016) does show a steady increase in production). In fact, comparing 2008 with 2017, demand production as well as final consumption of electricity declined by approximately 90 TWh, whereas import and export balances increased.

### 12.2.4 Electricity production from RES and biomass

While the overall quantity of generated electricity remained practically stagnant, the share of RES increased, when analysing the origins of electrical

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[22] `https://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_production,_consumption_and_market_overview`

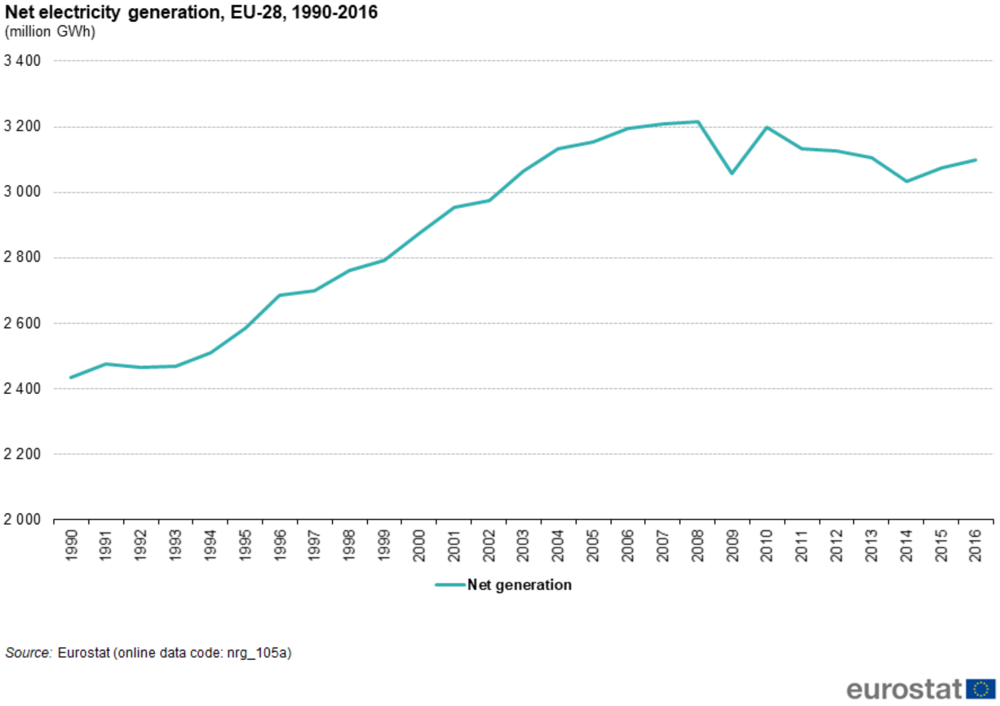

Figure 15: Net electricity generation in million GWh, EU-28, 1990-2016

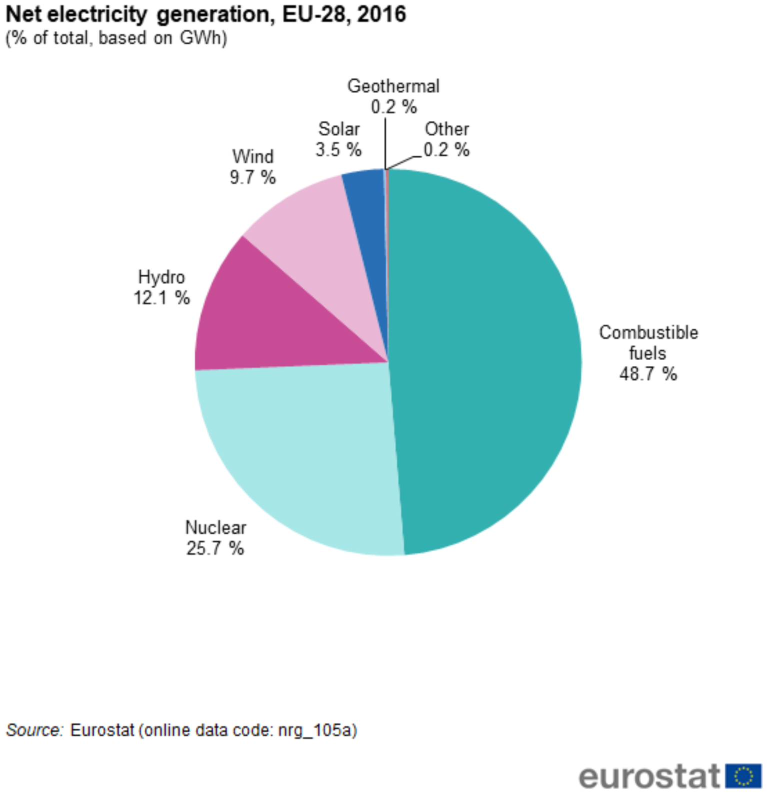

Figure 16: Net electricity generation in %-share of different energy sources, EU-28, 2016

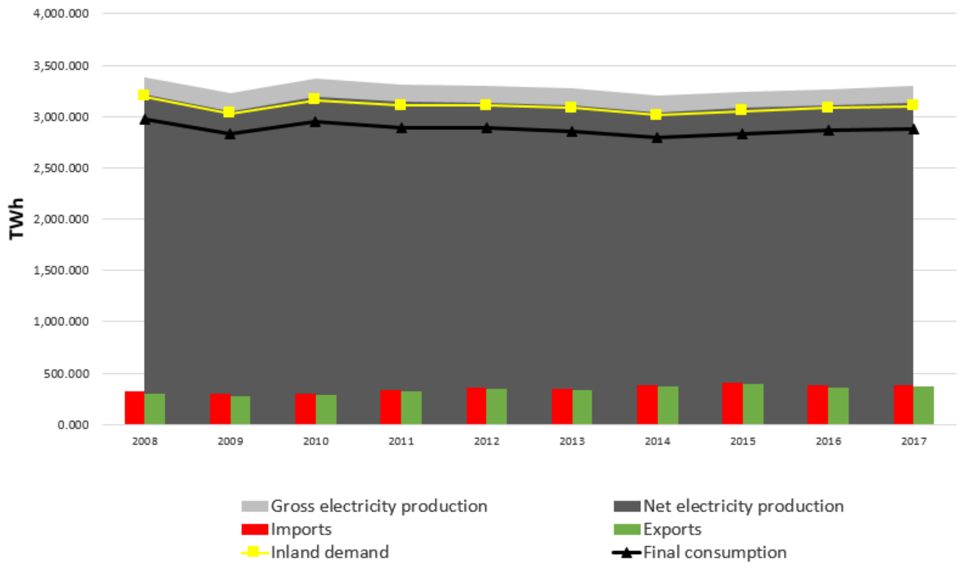

Figure 17: Demand, production and consumption of electricity in GWh, EU-28, 2008-2016 (source: Table 11)

Table 11: Demand, production and consumption of electricity in TWh, EU-28, 2008-2016 (source: EUROSTAT, online data code nrg-cb-e)

| | **2008** | **2009** | **2010** | **2011** | **2012** |
|---|---|---|---|---|---|
| **Inland demand** | 3,193.624 | 3,032.401 | 3,161.347 | 3,107.565 | 3,107.847 |
| Gross production | 3,387.311 | 3,222.372 | 3,366.584 | 3,309.916 | 3,304.155 |
| Net production | 3,215.745 | 3,056.109 | 3,198.270 | 3,140.469 | 3,133.640 |
| Avail. for final cons. | 2,974.497 | 2,823.426 | 2,948.903 | 2,897.266 | 2,896.342 |
| **Final consumption** | 2,973.306 | 2,826.447 | 2,946.716 | 2,886.111 | 2,884.607 |
| Imports | 317.422 | 298.886 | 298.683 | 329.805 | 363.229 |
| Exports | 294.347 | 278.742 | 291.123 | 322.615 | 344.580 |
| | **2013** | **2014** | **2015** | **2016** | **2017** |
| **Inland demand** | 3,082.462 | 3,009.347 | 3,052.971 | 3,082.577 | 3,101.979 |
| Gross production | 3,278.862 | 3,199.279 | 3,244.181 | 3,266.707 | 3,299.192 |
| Net production | 3,115.231 | 3,039.431 | 3,082.987 | 3,108.480 | 3,137.871 |
| Avail. for final cons. | 2,870.845 | 2,807.104 | 2,845.721 | 2,876.807 | 2,895.807 |
| **Final consumption** | 2,859.081 | 2,792.406 | 2,834.201 | 2,865.861 | 2,881.882 |
| Imports | 349.594 | 386.931 | 410.600 | 382.541 | 384.736 |
| Exports | 336.984 | 371.433 | 396.169 | 364.151 | 374.537 |

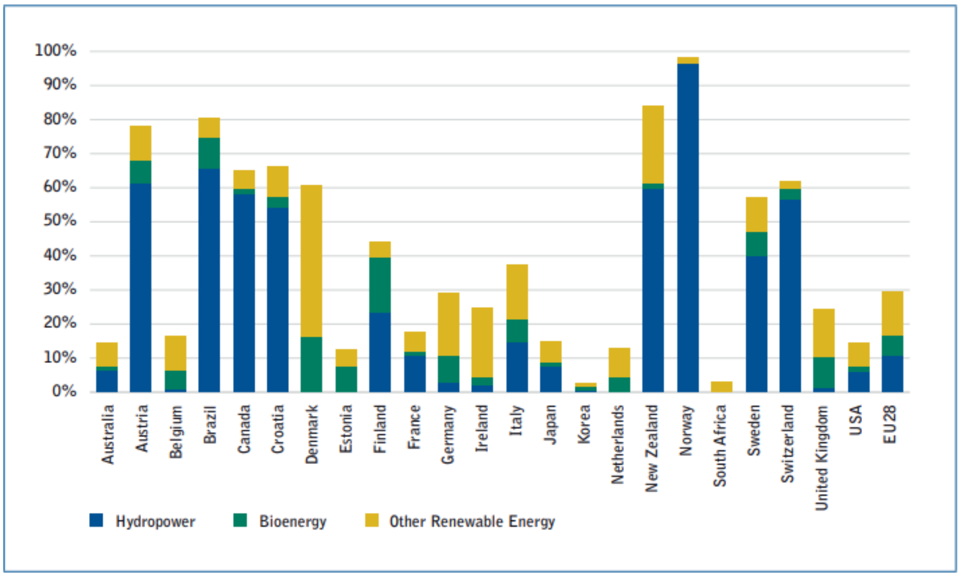

Figure 18: Shares of Renewables in total electricity production, global comparison, 2016 (source: IEA (2018)[Figure 3])

energy. The changes of gross electricity generation from RESs over time are presented in Figure 19 and Figure 20.

In 2016, 29.6% of the gross electricity consumption in the EU-28 was generated through RES, among which hydro followed by wind form the most important technologies, according to EUROSTAT[23].

The breakdown of all RE carriers is depicted by Figure 19. It shows a stable share of hydro, while wind power has had significant increases. A steady increase can be observed for biomass (aggregated solid, liquid, gaseous and wastes) as well over 26 years, in contrary to solar power, which has increased in a similar strength, however in less than 15 years. Figure 20 focuses on showing the shares of RESs and biomass compared to the total gross production of energy: the left part depicts the relation between biomass, total Renewables and total gross production of electricity, while the right part is a further breakdown of biofuels (a close-up of the biomass-area shown in the left part). Note that this is not a stacked chart; therefore it shows the significance of solid biofuels (e.g. wood), which represent approximately 50% of the total amount biofuels for electricity generation. Second most important are biogases, which in fact have experienced a stronger increase than solid biofuels. Liquid biofuels as well as renewable waste have a subordinate and rather stable role in regards to electricity production.

The appendices contain extended views from EUROSTAT, for gross electricity production per fuel in the EU-28 (Table 19) and the shares of RESs in gross final consumption of electricity per country (Table 20).

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[23] https://ec.europa.eu/eurostat/statistics-explained/index.php/Renewable_energy_statistics

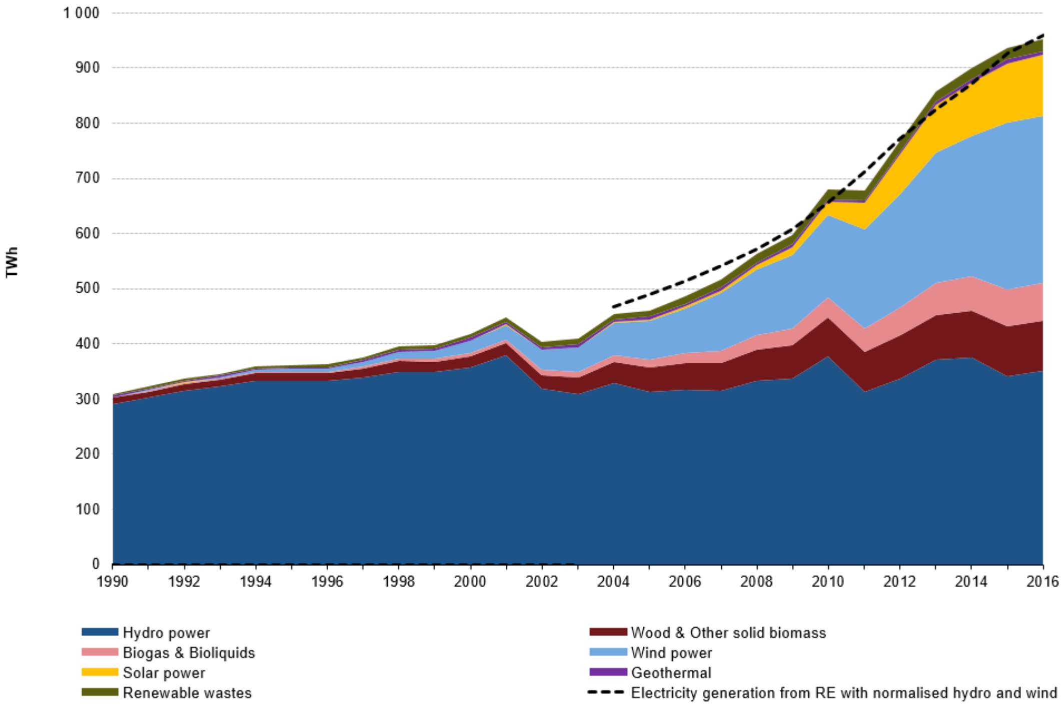

Figure 19: Gross electricity generation from renewable sources in TWh, EU-28, 1990-2016 (source: EUROSTAT, online data code: nrg 105a)

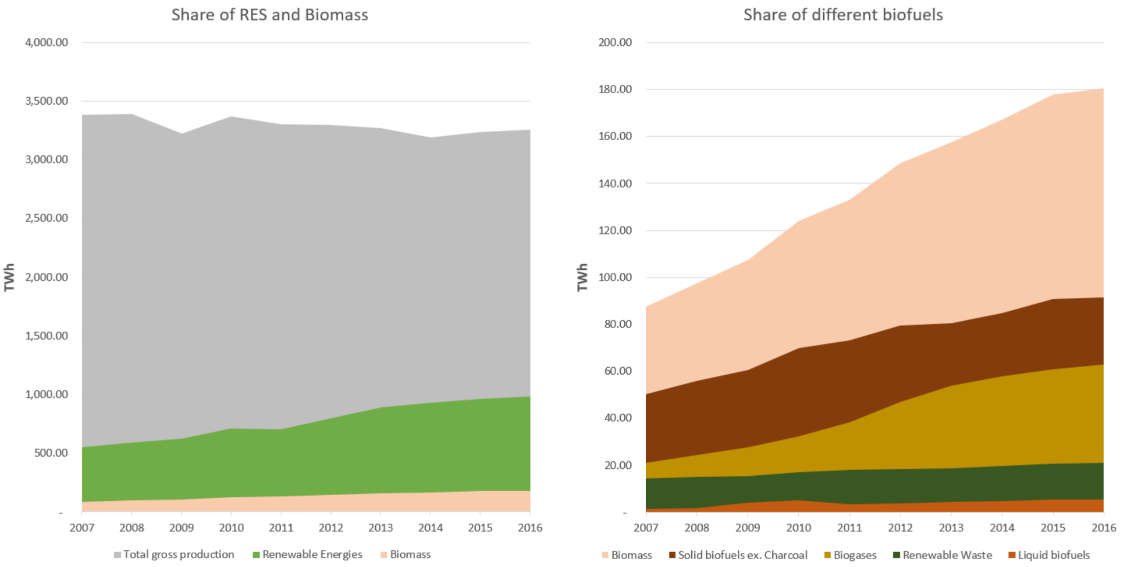

Figure 20: Gross electricity generation from biomass in TWh, EU-28, 2007-2016 (source: Table 12)

Table 12: Gross production of electricity in GWh, EU-28, 2007-2016 (source: EUROSTAT, data code nrg 105a)

| | **2008** | **2010** | **2012** | **2013** | **2014** | **2015** | **2016** |
|---|---|---|---|---|---|---|---|
| Final Energy consumption | 2,862.53 | 2,838.24 | 2,800.38 | 2,777.37 | 2,711.78 | 2,751.93 | 2,784.28 |
| **Total gross production** | **3,387.34** | **3,366.59** | **3,296.15** | **3,270.87** | **3,191.16** | **3,235.24** | **3,255.05** |
| Solid fossil fuels | 899.66 | 829.20 | 900.74 | 874.54 | 807.86 | 791.82 | 701.28 |
| Crude oil and petroleum products | 108.26 | 86.90 | 71.48 | 61.22 | 58.05 | 60.98 | 59.51 |
| Natural Gas and derived gases | 825.87 | 799.42 | 617.57 | 543.90 | 491.01 | 530.34 | 642.27 |
| Nuclear | 937.22 | 916.61 | 882.37 | 876.83 | 876.30 | 857.13 | 839.68 |
| Waste (non-renewable) | 16.77 | 19.05 | 20.57 | 20.37 | 21.88 | 23.13 | 25.86 |
| Others | 4.86 | 4.60 | 4.82 | 4.69 | 4.87 | 6.11 | 4.96 |
| **Renewable Energies** | **594.70** | **710.81** | **798.58** | **889.29** | **931.18** | **965.71** | **981.47** |
| **of which Biomass** | **97.40** | **124.07** | **148.55** | **157.42** | **167.14** | **177.76** | **180.46** |
| Solid biofuels ex. Charcoal | 56.00 | 69.98 | 79.48 | 80.63 | 84.87 | 90.74 | 91.44 |
| Biogases | 24.38 | 32.15 | 47.00 | 53.82 | 57.86 | 61.01 | 62.71 |
| Renewable Waste | 15.15 | 16.97 | 18.47 | 18.71 | 19.59 | 20.52 | 21.05 |
| Liquid biofuels | 1.86 | 4.97 | 3.60 | 4.26 | 4.82 | 5.48 | 5.27 |
| *RES/TOTAL gross production* | *17.56%* | *21.11%* | *24.23%* | *27.19%* | *29.18%* | *29.85%* | *30.15%* |
| *Biomass/RES gross production* | *16.38%* | *17.45%* | *18.60%* | *17.70%* | *17.95%* | *18.41%* | *18.39%* |
| *Biomass/TOTAL gross production* | *2.88%* | *3.69%* | *4.51%* | *4.81%* | *5.24%* | *5.49%* | *5.54%* |

# 13 Promotion and development of RES-E and in particular biomass: the case of Austria

As a consequence of the EU Renewable Energy Directive (RED), the Republic of Austria has set out a legal framework called "Green Electricity Act". It builds the legal base of policies and support schemes for RES-E and serves the purpose of reaching the NREAP targets. Austria has been assigned a target of 34% share of RES in total energy consumption. For the electricity sector, the NREAP had stated a target of 70.6% RES share of final consumption.

This section will outline main aspects of the Austrian legal framework concerning Electricity from Renewable Energy Sources as well as Renewables support in Austria, followed by an overview of biomass-for-electricity installations and outlook.

## 13.1 National legal framework concerning Electricity in Austria

Different entities, ordinances and legal acts form a legal framework and responsibility matrix regarding all aspects of electricity in Austria. Major involved entities are:

- Federal and National Councils of the Republic of Austria, who pass laws such as the below mentioned acts in this section
- Federal Ministry for Sustainability and Tourism (or *Bundesministerium fuer Nachhaltigkeit und Tourismus (BMNT)* in German), who passes several ordinances related to RES-E such as the below mentioned ordinances in this section
- E-Control, the regulatory body, who is monitoring the electricity market and RES-E targets among other parameters such as GO, and who is also entitled for certain ordinances towards actors of the electricity market
- The Green Electricity clearing and settlement agency OeMAG, who is responsible for granting FITs to eligible plant operators, and generally monitor and coordinate RES-E support within the foreseen annual budgets and extents.

### 13.1.1 The Electricity Act (*ElWOG*)

The Electricity Act from 2010, or *Elektrizitaetswirtschafts- und Organisationsgesetz (ElWOG)* in German (Republik Österreich, 2010), is the central legal act around provisioning electricity in Austria.

The ElWOG formulates the base for electricity generation, trading, provisioning, supply, operations of facilities and power quality and other aspects, with the main objectives formulated as follows:

- Provisioning Austria with electricity of high standards to affordable prices
- Establishing an electricity market in accordance with EU law

- Establishing and maintaining the security, stability and sustainability of supply and grid
- Promoting Electricity from Renewable Energy Sources (RES-E)
- Acting in the common interest of public and economy
- Entitling E-Control Austria[24] to monitor and control the electricity market

It also transposes EU law, namely the directives for internal energy market (2009/72/EG), CHP (2004/8/EG) and energy efficiency (2006/32/EG).

### 13.1.2 The Green Electricity Act (*ÖSG*)

The Green Electricity act from 2012, or *OeSG* in German (Republik Österreich, 2012), embodies the transposition of EU law, mainly the RED (9.3), and in addition the Directives concerning the internal electricity market (2009/72/EC) and energy efficiency (2006/32/EC).

Following is a list of the main aspects, defined and codified by this federal law:

- Scope, objectives, references to EU law (which it transposes)
- Grid connection of plants
- Accreditation of plants and contractual obligations between applications and plant operators
- Guarantee of Origins (GOs) and their recognition, in case from importing countries
- Technology specific support schemes and goals incl. yearly budget volume
- Statutory requirements for the eligibility to receive support
- Subsidies and purchase obligations
- Feed-in Tariff layout and details
- Follow-up tariffs for fuel- or feedstock-dependent plants
- Investment aid for plant construction
- Settlement agencies for all kinds of subsidies
- The settlement agent for green electricity and its tasks, duties and obligations
- Funding of the RES support scheme framework
- Classification and codification of types of waste eligible for power generation under the OeSG

With regards to support schemes, the *OeSG* details, which technologies and capacities are eligible for RES support. It nominates *Abwicklungsstelle für Oekostrom AG (OeMAG)* as the clearing and settlement agency for all RES support related transactions, its duties, responsibilities and rights. Finally, the *OeSG* also transposes the 2020 targets into national law and formulates technology specific goals for plant capacity increments. The goals are monitored by E-Control.

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[24] The energy regulatory authority in Austria is embodied by E-Control Austria, as such nominated through the Energy control act (E-Control Gesetz) in 2010.

### 13.1.3 Future laws and acts

The Green Electricity Act Amendment (*Ökostromnovelle*) from 2018 was accepted by the the Austrian Parliament in 2019 (Auer, 2019b) and extends the Green Electricity act mainly with follow-up tariff guarantees for biomass plants, of which support expires between 2017 and 2019. At the time this work was finalized, the amendment was not yet legally binding, as it was not yet accepted by the federal council (cf. section 13.6).

The "Mission 2030" from 2018 (cf. section 13.5) presents a strategy which is not legally binding. The Federal Council of Ministers has decided to elaborate the "Renewable Energy Extension Act 2020" (*Erneuerbare Energien Ausbaugesetz 2020*) which is supposed to address Mission 2030 and build on the Green electricity Act.[25] An essential expected change is the end of fixed Feed-in Tariffs in 2020, being replaced with market premiums awarded through tenders. (Auer, 2018)

### 13.1.4 Power Labelling Ordinance

The Power Labelling Ordinance, or *Stromkennzeichnungsverordnung* in German (Republik Österreich, 2011), treats the labelling of electricity units in terms of their origin. The system of electricity disclosure has been put in place already in 2001, and today is regulated by the Power Labelling Ordinance, which also entitles the E-Control Austria to monitor its effecting procedures.

It mandates all suppliers of electrical energy to declare the origin (primary energy sources) and emissions of $CO_2$ and radioactivity for each delivered MWh of electricity to for consumption. Each unit of electricity is registered with a GO certificate, and since 2015, electricity of unknown origin ("grey electricity") is prohibited.

The rules applicable to GOs, contents of disclosure statements are mainly defined in the Power Labelling Ordinance (2011), however the overall framework is established together with the Electricity Act and Green Electricity Act respectively. All GOs are stored in the GO-database (*Stromnachweisdatenbank*[26]), which includes imported electricity.

## 13.2 RES-E support in Austria

Austria mainly promotes Electricity from Renewable Energy Sources (RES-E) through a technology specific FIT (*Einspeisetarif* in German) support scheme, set out in the Green Electricity Act.[27]

### 13.2.1 Feed-in Tariff (FIT)

Generally, all common RES-E technologies are eligible to support through a FIT.

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[25] https://www.bmnt.gv.at/umwelt/energiewende/erneuerbare_energie/Erarbeitung-des-Erneuerbaren-Ausbau-Gesetz-beschlossen.html

[26] https://www.e-control.at/en/stromnachweisdatenbank

[27] http://www.res-legal.eu/search-by-country/austria

Plant operators are guaranteed (through contractual purchase obligations by the OeMAG) that they are reimbursed for electricity they produce for a granted period, provided that their plant is eligible for support. OeMAG, the green power clearing and settlement agency, is entitled to decide about eligibility as per the OeSG, and to ensure the promotional volume of the FIT is not exhausted.

If a FIT is granted to a generation plant, that is if it fulfils the statutory requirements for eligibility, OeMAG is contractually obliged to purchase the electricity generated by the supported plant. In turn, system operators are also obliged to distributed this energy, whose feed-in is prioritized over non-RESs. [28] Tariffs are laid down in the FIT Ordinance, or *Ökostrom-Einspeisetarif-Verordnung (ÖSET-VO)* in German, and regularly updated. For example, FITs for 2018 and 2019 were published in 2017 (ÖSET-VO 2018[29]).

**Successive rates** to FITs were introduced by a revision of the OeSG in 2017, as an incentive for highly efficient biogas fired power plants. Depending on their efficiency, plants may be eligible to this special tariff for a limited time (five years).

**Criticism** The current RES-E support schemes are not market oriented, which is a fact that has been criticised from an economic perspective, not only in Austria, but in all EU countries which have adopted similar concepts. (Urschitz, 2018) Missing market orientation and lack of degression, and efficiency dependant incentives especially leads biomass into a difficult situation, as elaborated below in section 13.6.

### 13.2.2 Investment aid

Investment aid is granted in form of subsidies to installations which are not eligible to a FIT. Those are small- and medium-scale hydro power plants (500kW through 10MW capacity) and PV installations on buildings or in the agriculture sector with capacities between 5 and 200 kW.

### 13.2.3 Biomass

In regards to solid and liquid biomass as well as biogas, an increment of 200 MW in capacity was targeted between 2010 and 2020, according to OeSG. This represents 1.3 TWh of additional average electricity output expected per year.

A budget volume of €10 million per year was foreseen for this purpose, of which €3 million were reserved specifically for power plants fired with solid biomass and with a maximum capacity of 500 kW, and a maximum of €1 million for biogas plants. With the amended [30]

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[28] `https://www.e-control.at/en/marktteilnehmer/oeko-energie/oekostrom-foerdersystem`

[29] `https://www.ris.bka.gv.at/Dokumente/BgblAuth/BGBLA_2017_II_408/BGBLA_2017_II_408.html`

[30] `https://www.oem-ag.at/de/foerderung/biogas-biomasse/`

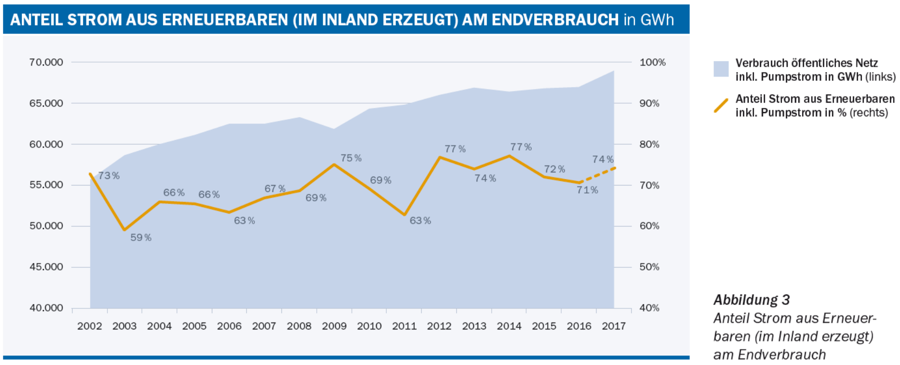

*Abbildung 3*
*Anteil Strom aus Erneuerbaren (im Inland erzeugt) am Endverbrauch*

*Quelle: E-Control*

Figure 21: Share of RES-E (from domestic production) in final consumption in GWh, Austria, 2002-2017 (source: (e control, 2018b)[Fig. (Abbildung) 3])

The FIT for biomass and biogas plants is granted for a period of 15 years, contrary to all other eligible RES-E plants, which receive 13 years of guaranteed purchases. Given the diversity of the expression “biomass”, the OeSG furthermore specifies biomass feedstock types in a detailed way.

**Follow-up tariffs** for fuel- or feedstock-dependant RES-E power plants, such as biomass, are defined by the OeSG. Eligible plants may be granted an extension of the the purchase obligations by OeMAG, in case it has expired, provided availability of additional annual support funds, reserved for this purpose. The extension is possible one time only, and limited to 60 months. The biogas follow-up tariff ordinance (or *Biogas-Nachfolgetarifverordnung* in German) from 2017 has constated tariffs for biogas plants only.[31] As part of the Green Electricity Act Amendment (cf. section 13.1.3), biomass plants are to be considered as well.

### 13.2.4 Impact of the Green Electricity Act (OeSG)

Effects of the Green Electricity Act (OeSG) are depicted in Figure 23, which shows the capacity increase of RES-E plants in the period 2008 through 2018, covering all installations resulting from OeMAG support. The source data can be found in Table 13 (source: OeMAG[32]) and shows that wind energy has experienced the strongest increase among all subsidies RESs.

From 2011 to 2018, the installed capacity of eligible plant types has more than doubled and generate 17.9% of the power in Austria (final consumption). In 2017, 25,365 installed RES-E plants under OeMAG contracts had a total installed capacity of 3,798 MW, feeding 10,527.7 GWh into the grid. (e control, 2018b)[Table 2]

The Green electricity report also expresses the share of Renewables in final consumption of electricity, from domestic generation, shown in Figure 21. The light blue area represents the final grid consumption (incl. electricity from pump storages) in GWh, while the dark yellow line indicates the share (in %)

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[31] `https://www.ris.bka.gv.at/Dokumente/BgblAuth/BGBLA_2017_II_201/BGBLA_2017_II_201.html`

[32] `https://www.oem-ag.at/de/oekostromneu/installierte-leistung`

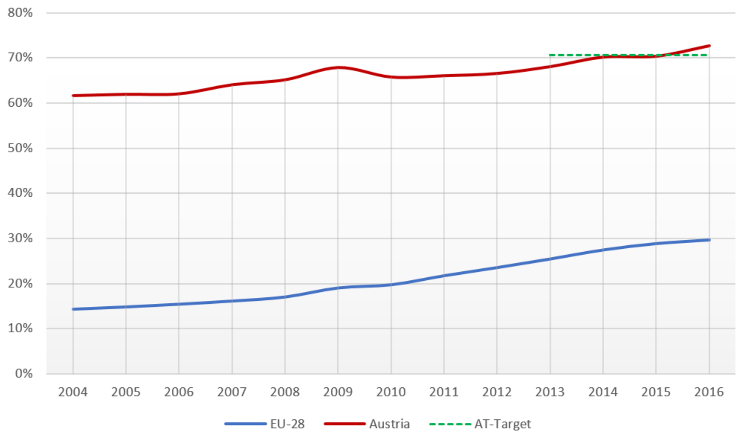

Figure 22: Share (in %) of RES in final consumption of electricity, Austria and EU-28, 2004-2016 (source: Table 20)

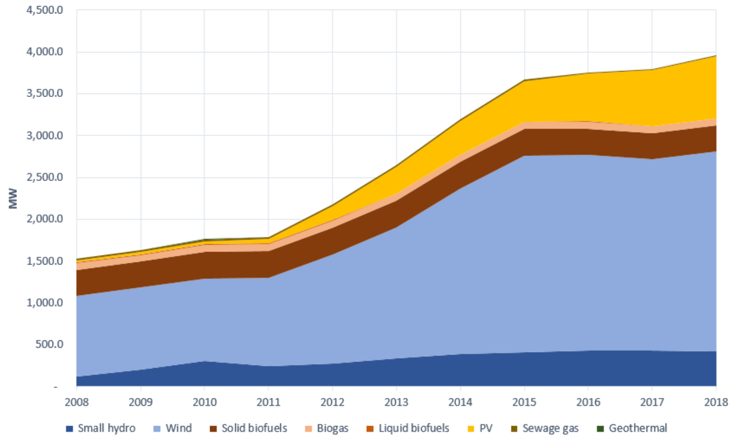

Figure 23: Installed capacity of supported RES through the Green Electricity act in MW, Austria, 2008-2018 (source: Table 13)

of RES (the dotted part indicates projections). It shall be highlighted that this chart explicitly addresses RES-E originated from domestic production. (e control, 2018b)

Austria has exceeded its sectorial targets for RES-E already by 2015. In comparison with other countries as well as with the overall EU-28, the share of RES-E was comparably high prior to the RED. Figure 22 shows the development of RES-E in terms of final electricity consumption, and compares Austria with the EU-28. A full dataset of all MSs is found in Table 20 in the Appendices.

## 13.3 Statistics about electricity in Austria

For terms, definitions and general notes on interpreting electricity statistics refer to section 12.2.1.

The Austrian Electricity disclosure report published by e-Control, is con-

Table 13: Installed capacity of supported RES through the Green Electricity act in MW, Austria, 2008-2018 (source: OeMAG)

| | **2008** | **2009** | **2010** | **2011** | **2012** | **2013** | **2014** | **2015** | **2016** | **2017** | **2018** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Small hydro | 124.7 | 200.9 | 303.8 | 242.2 | 276.0 | 342.3 | 390.9 | 413.8 | 427.7 | 429.5 | 419.6 |
| Wind | 960.9 | 984.1 | 988.2 | 1,055.8 | 1,306.8 | 1,555.4 | 1,980.6 | 2,349.1 | 2,346.6 | 2,290.5 | 2,390.2 |
| Solid biofuels | 311.7 | 313.4 | 324.9 | 325.4 | 319.8 | 321.5 | 318.6 | 315.0 | 311.0 | 311.5 | 312.4 |
| Biogas | 76.2 | 77.0 | 79.2 | 79.8 | 81.2 | 82.5 | 80.5 | 81.3 | 83.3 | 84.4 | 85.7 |
| Liquid biofuels | 14.5 | 9.6 | 9.4 | 9.4 | 8.7 | 5.0 | 2.8 | 2.8 | 1.5 | 1.3 | 1.1 |
| PV | 21.7 | 26.8 | 35.0 | 54.7 | 172.1 | 323.9 | 404.4 | 489.3 | 568.0 | 665.9 | 739.4 |
| Sewage gas | 21.2 | 21.1 | 21.2 | 16.0 | 16.6 | 15.8 | 14.3 | 14.7 | 14.8 | 14.5 | 14.2 |
| Geothermal | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 |

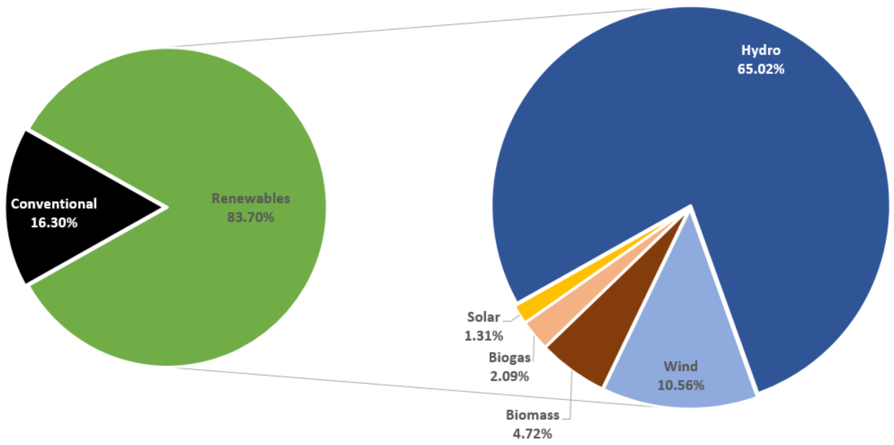

Figure 24: Share of Renewables in final electricity distribution (consumption) in Austria, 2017 (source data: e control (2018c))

cerned with electricity provided to consumers by suppliers (includes imported energy). Information is based on GOs and disclosure statements of the suppliers. According to this E-Control, the share of RES-E in 2017 distributed electricity was at 83.71%, cf. also Figure 24. A slight decline of the Renewables share in favour of fossil fuels has been observed compared to 2016, where it was 86.74%. However, it shall be noted that this concerns finally distributed and consumed energy, which is a mix of domestic production and imported energy. (e control, 2018c)

In terms GOs per country, the share of Austria has increased from 70.08% in 2016 to 73.91% to 2017, which could indicate fluctuating regional demands for electricity. A comparison between disclosure of RES-E and physical domestic generation shows that an approximate of 84% of disclosed electricity in Austria is from Renewables, whereas the share of domestic generation from RES is only at 74%. (e control, 2018c)

Figure 25 depicts the 2017 share of different RESs technology types in the gross electricity production of Austria. The area “Total RES” represents the sum of Wind, PV and Geothermal power generation. Details and a further breakdown can be found in Table 14). Hydro was and is the predominant power generation technology in Austria (2017), representing almost 60% of the gross domestic production, followed by 22% from fossil fuels (mainly natural gas), while Renewables and biomass are represented with less than 20%.

The balance of electricity generation and imports with electricity available for final consumption between 1990 and 2017 is depicted by Figure 26 and listed in Table 16. A steady rise of electricity generated and consumed can be observed as well as an increasing share of physical imports on account of gross domestic production. A possible explanation is the energy union and implementation of an integrated market. The detailed breakdown of how total inland consumption, pump storage and physical exports build an equilibrium with the total gross generation of electricity can be found in Table 15, for the years 2016 and 2017.

Figure 27 presents the trend of final consumption of electricity in Austria since 1990, showing as well a steady increase.

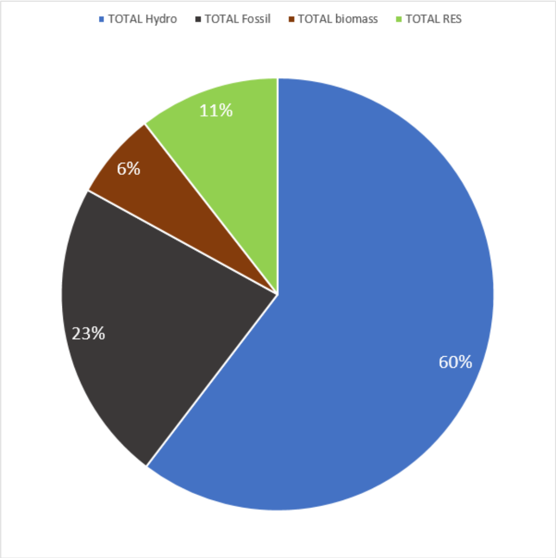

Figure 25: Share of RES plant types in gross electricity production in Austria, 2017 (source: Table 14)

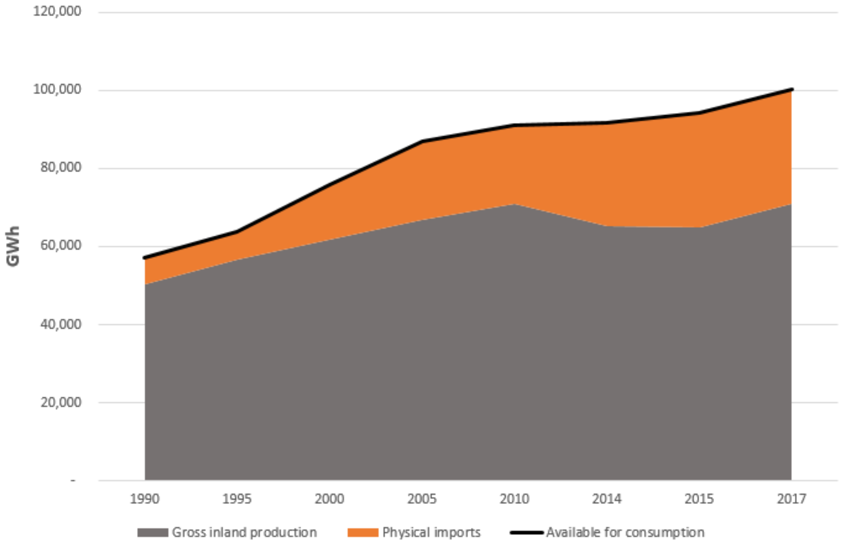

Figure 26: Balance of electricity production, imports and consumption in GWh, Austria, 1990-2017 (source: Table 16)

Table 14: Gross electricity production in GWh and share of total amount, from different plant types in Austria, 2017 (source: e control (2018a))

| | **Plant type** | **GWh** | **Share** |
|---|---|---|---|
| Hydro | Run-of-river | 28,877 | 40.8% |
| | Pump storage | 13,211 | 18.7% |
| | **TOTAL Hydro** | **42,088** | **59.4%** |
| Fossil | Coal fuels | 3,915 | 5.5% |
| | Oil fuels | 783 | 1.1% |
| | Natural gas | 11,064 | 15.6% |
| | **TOTAL Fossil** | **15,763** | **22.3%** |
| Biomass | Solid biofuels | 2,523 | 3.6% |
| | Liquid biofuels | - | 0.0% |
| | Biogas | 595 | 0.8% |
| | Sewage gas | 35 | 0.0% |
| | Other biomass | 1,366 | 1.9% |
| | **TOTAL Biomass** | **4,519** | **6.4%** |
| RES | Wind | 6,569 | 9.3% |
| | PV | 767 | 1.1% |
| | Geothermal | - | 0.0% |
| | **TOTAL of other RESs** | **7,337** | **10.4%** |
| | Others | 1,116 | 1.6% |
| **TOTAL gross production** | | **70,823** | **100.0%** |

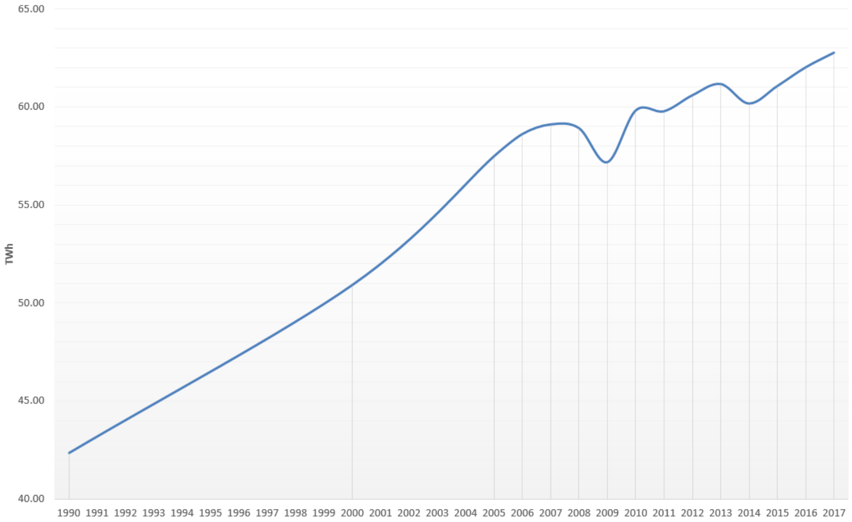

Figure 27: Final electricity consumption in TWh, Austria, 1990-2017 (source: Statistik Austria, Bilanz der Elektrischen Energie 1970 bis 2017)

Table 15: Balance of electricity production and consumption in GWh, Austria, 2016-2017 (source: e control (2018a))

| | 2016 | 2017 | Delta |
|---|---:|---:|---:|
| Final consumption | 65,373 | 66,274 | 901 |
| Grid losses | 3,342 | 3,459 | 117 |
| Plant consumption | 2,025 | 2,090 | 65 |
| **Total inland consumption** | **70,740** | **71,824** | **1,084** |
| Pump storage | 4,339 | 5,545 | 1,206 |
| *Physical exports* | 19,207 | 22,817 | 3,610 |
| **Available for consumption** | **94,286** | **100,185** | **5,899** |
| *Physical imports* | 26,366 | 29,362 | 2,996 |
| **Total gross generation** | **67,919** | **70,824** | **2,905** |
| Generation hydro plants | 42,916 | 42,088 | - 828 |
| Generation heat plants | 19,043 | 21,272 | 2,229 |
| Generation RES (PV, Wind, Geoth.) | 5,900 | 7,337 | 1,437 |
| Generation others | 60 | 127 | 67 |

Table 16: Balance of electricity production, imports and consumption in GWh, Austria, 1990-2017 (source: e control (2018a))

| | **1990** | **1995** | **2000** | **2005** |
|---|---|---|---|---|
| Gross inland production | 50,413 | 56,587 | 61,798 | 66,735 |
| Physical imports | 6,839 | 7,287 | 13,920 | 20,355 |
| Available for consumption | 57,252 | 63,874 | 75,718 | 87,091 |
| | **2010** | **2014** | **2015** | **2017** |
| Gross inland production | 71,070 | 65,134 | 64,762 | 70,823 |
| Physical imports | 19,909 | 26,712 | 29,389 | 29,362 |
| Available for consumption | 90,979 | 91,846 | 94,151 | 100,185 |

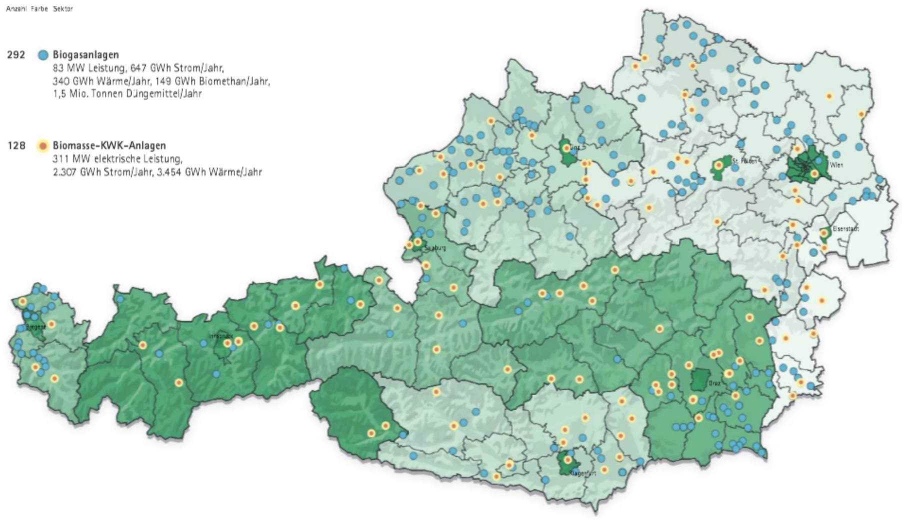

Figure 28: Distribution of Bioelectricity plants in Austria (blue dots indicate biogas, remaining indicate CHP plants

## 13.4 The role of bioenergy in Austria

Biomass has a comparably low significance to electricity production, as it bears a higher technology specific risk (raw material dependencies) and biomass plants involve higher complexities in operation. Today, the major utilization of biomass feedstock is heat, for industry and buildings, followed by CHP. Within the category biomass, solid biofuels such as wood represent the major part. (Haas et al., 2017)

Table 25 shows that with 6.4% share of the total gross electricity production in Austria, biomass plays a subordinate role compared to hydro and fossil fuels. However, in represents more than half of wind and PV together. The main share of biomass comes from solid biofuels. In contrast, the share of biomass in final electricity distribution (including imports) was at 4.72% in 2017 (cf. Figure 24).

The installed capacity induced through subsidies over time, as depicted in

Figure 23, does not show significant increases when it comes to biomass. In fact, the trend of solid, liquid biofuels and biogases was declining for the last decade almost. In 2017, 134 solid biomass power plants formed an installed capacity of 311.49 MW, in contrast of 288 biogas plants at a capacity of 84.4 MW. (e control, 2018b)

With the amendment of the Green Electricity Act (*Kleine Ökostromnovelle*) in 2017 mandates, E-Control is furthermore commissioned to include in the yearly Green Electricity Report (*Ökostromreport*) an assessment of feedstock supply concepts for all power plants operated partly or completely with biomass and biogas fired, and at least for the first 5 years of operation. Furthermore, the concept shall outline the sources (regional, national, import) of raw materials. At the time this work was finalized, the latest published Green Electricity Report from 2018 did not provide a full view; and was limited to a review of 20 power plants. 18 out of those 20 were operated with solid biomass, out of which 2 are fired solely with the operator's own raw material, and 6 use raw material from local/regional forestry (25 km radius). All remaining plants are operated exclusively with purchased raw material, of which the origins were not declared. (e control, 2018b)

### 13.4.1 Potential/outlook

Projections of Oesterreichischer Biomasseverband (OeBMV)[33] suggest that under existing resource scenarios, the production of RES-E from solid biomass and biogas can be extended 48%, by installing additional CHP plants with electrical capacity of 300 MW. This would result in additional feed-in volume of approximately 6,500 GWh per year.

Despite amendments in favour of biomass (Follow-up tariffs, cf. section 13.2.3), the OeBMV criticises the OeSG, stating its insufficient and inefficient support schemes with regards to biomass. They suggest that a significant part of operating biomass plants would need to be shut down, unless the law is amended and improves the role of biomass electricity in Austria: follow-up investments for efficient installations, a promotion scheme that allows flexible production and supply, and overall a support scheme that ensures that biomass plants can be economically operated until reaching their technical end of life.

The recommendation of OeBMV is furthermore to enforce usage of biomass and waste operated CHP plants with additional 300 MW of electrical capacity until 2030, on an on demand basis throughout the year, particularly in winter (to substitute lower PV and hydro volumes). Also, focus should lie in small, decentralized plants up to 500 kW capacity, in order to ensure regional power supply, grid stability and positive economic effects.

(Haas et al., 2017) analyse whether moving towards an electricity supply system comprising of 100% in final consumption is technically feasible. They conclude that under their RES-Scenario, it is both technically feasible and economically more attractive than in a scenario with high fossil share. In their scenario, they calculate a remaining 145 PJ of energy demand from feedstock-oriented combustion plants to guarantee supply stability. Of this plant group, the share of biofuels could be increased from 30 to 59% on the

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[33] `https://www.biomasseverband.at/bioenergie/energie-aus-biomasse/strom/`

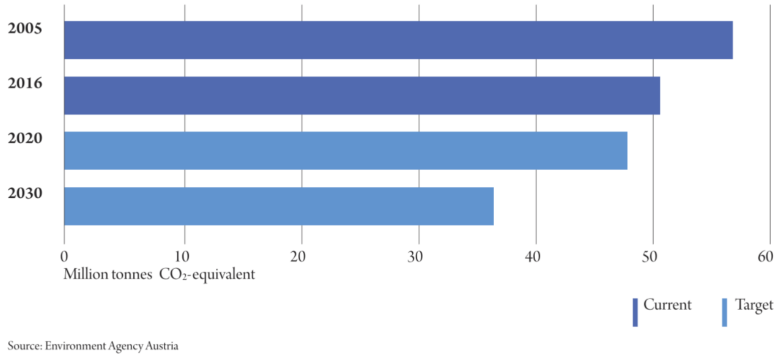

Figure 29: Non-ETS GHG emissions trajectory, Austria (source: (BMNT and BMVIT, 2018))

account of fossil fuels. It is suggested that an electricity system solely relying on volatile RESs bears a high risk; which is why the share of bioenergy would be significantly increase. Extensive use of volatile sources require additional pump storages, which are claimed to be more invasive to nature and more cost intensive than biomass plants. Another important aspect are load peaks, which are difficult to be provided by hydro or volatile RESs, whereas bioenergy heat plants are regarded as well capable of supplying peak energy on demand, which today is fulfilled to a big portion by conventional plants. However, the overall contribution of bioenergy in the electricity sector is predicted to remain comparably low.

## 13.5 Mission 2030: The Austrian Climate and Energy Strategy

With the "*Mission 2030*" (BMNT and BMVIT, 2018), Austria's Federal Ministries for Sustainability and Tourism *BMNT* as well as Transport, Innovation and Technology Bundesministerium fuer Vekehr, Innovation und Technologie (BMVIT) address and define the pathway to reaching climate and energy targets by 2030 and beyond. Central motivation is the reduction of GHG emissions by 36% in 2030, compared to 2005 (cf. Figure 29), covering both ETS as well as non-ETS sectors. Coupled with existing EU targets (cf. section 9.2), *Mission 2030* describes tasks to reach the country's targets, and lists instruments as well concrete projects to facilitate them For the energy sector, Austria has set itself the goal to reach fully decarbonize by 2050, through switching from fossil fuels to RESs. By 2030, it is planned to increase the share of RES in gross final consumption of energy to 50%; today it is 33.5%, almost at the 2020 target of 34%. (BMNT and BMVIT, 2018)

### 13.5.1 Electricity sector

As to electricity, Austria's objective is to generate *100% of the total domestic consumption* from inland RESs, also taking into account the projected increase in consumption (induced by other sectors such as mobility.) A major concern and motivation to promote RES-E even further is the security of supply and a partial dependency of electricity imports. One of the mission objectives is also the elimination of this dependency. With all efforts to increase Renewables, financial support instruments also make part of the action plan, addressing increased investments not only the expansion of RES-E powered conversion plants, but furthermore in transmission and distribution grids and storage infrastructure, which are consequently required. In essence, the grid and storage infrastructure development must be synchronized with the RES-E expansion. For instance, concrete actions summed up in the "100,000 roof-mounted PV and small-scale storage programme" include additional tax benefits of private generation to enable more installations, while financially supporting hydrogen-electricity storage systems (e.g. electrolyse), which are needed to store the excess production of electricity.

Biomass is stated to have a subordinate role in the inland production of electricity, for which hydro, followed by wind and PV are identified to be the diving forces. In fact, the potentials for this form of energy are accounted mainly to decentralized energy systems, in particular heating or CHP. As such, biogas would be essential in regards to "greening the gas", i.e. replacing a large proportion of natural gas with renewable methane. The main concern and motivation to promote Renewables in the heat sector is its strong dependency on imported fossil fuels. However, biomass is regarded as important source for demand-driven production of both heat and power, especially in integrated energy systems with coupled power, heat, mobility and industry sectors, and for decentralized regional energy. (BMNT and BMVIT, 2018)

Overall, *Mission 2030* addresses many aspects that fall under consideration when working towards its targets. E-Control criticize however that, while the "100% RES-E goal" builds an integral element of the mission statement, it is not transposed into law at all (yet). They claim that the existing legal framework of RES-E support will not suffice for reaching this target. This is well in line with conclusions of Haas et al. (2017), who also identify the strong need of additional framework requirements. Under the assumption the RES-E expansion continues at the same velocity as in the past, E-Control project an annual increase in domestic electricity generation of only around 1,000 GWh, eventually leading to approximately 10,000 GWh by 2030. However, depending on assumptions and scenarios, the 100% target would in any case require an approximate 30,000 GWh additional production. (e control, 2018b)

## 13.6 Recent events: Green Electricity Act Amendment

In light of expiring support grants for RES-E installations, particularly biomass fired power plants are at risk to force-close, as their operation is not cost-covering without financial support. In a wake-up call, the OeBMV and a large number of plant operators state that due to a significant difference between cost of generation (0.13 €/kWh) and market selling price (0.05-0.06 €/kWh, subject to fluctuations between 0.03 and 0.08 €), not less than two thirds of wood fired power plants would be forced to shut-down after their FIT guarantees expired, unless the government takes action. (APA, 2018)

As a consequence, an Amendment to the Green Electricity Act (called (*Ökostromnovelle*)) was proposed and accepted by the Austrian Parliament in January 2019. The amendment guarantees follow-up tariffs for a period of three years to biomass installations, of which the contractual sell/purchase obligation with OeMAG expires during the years of 2017-2019, by reserving a budget of 140 million Euros. With a per kWh cost of biomass electricity twice as high as the spot market price, even amortised installations are not capable of continuing cost-covering operation, experts say. The follow-up tariffs would "save" 45 plants from being decommissioned, and their lost generation volume being substituted by (imported) electricity. (Auer, 2019b)

The Green Electricity Act Amendment received strong criticism from political as well as industrial stakeholders, among which even biomass plant operators. Major point criticised by the opposition party is the lack of transparency and insufficient information, e.g. which plants are eligible to follow-up tariffs and under which conditions. The Amendment foresees follow-up support only for plants with efficiency classes above 60%. Critics claim that this is per definition inconclusive, and different experts come to varying conclusions about which and how many plants acutally fall into this category; which leads to the obvious question of how the budget can be justified. In consequence, the opposition party intends to block the final ratification of this amendment in the Federal Council[34], unless the act was amended or even recalled. (APA, 2019; Auer, 2019a)

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[34] As per Austrian legislation, acts which are accepted by a majority of the National Council in the parliament, become legally binding only after the Federal Council (*Bundesrat*) ratifies them as the final instance.

# 14 Discussion and conclusions

The present work has employed literature reviews and gathering of statistical data with the attempt to assess the role of biomass as a Renewable Energy Source (RES) for the generation of electricity in the EU. It comprises of four major topical areas:

1. Climate and energy strategies inducing the promotion of Renewable Energy, the consequent incentive policies and support mechanisms, as well as other legal frameworks
2. Biomass (in particular wood) as commodity and RES, its potential and barriers for energy/electricity utilization
3. The planned and actual extents of electricity generation plants operated with biomass
4. Austria as a focus area: legal and support frameworks, strategies and status of Renewables/biomass

## 14.1 Climate and Energy targets

Section 9 presents the timeline of EU climate strategies, their interrelations with global strategies, most importantly the Kyoto protocol, and how they evolved over time. Put in place in 2009, the Renewable Energy Directive (RED) and accompanying documents represented a the core framework to support the EU's mission. Since then, targets have been imposed on on Member States (MSs) in order to reach the set goals as a community. The way strategies were presented changed over the course of time.

While the RED was a directive with concrete binding targets for each EU member, including rules and penalties, harmonized reporting frameworks as well as guidance on support schemes; the subsequent communication packages were less directive and more suggestive. The 2030 targets in turn were established as community targets for "more flexibility of the MSs", in a "framework" rather than a package. This may be interpreted as more defensive and much less directive instructions, which is even enforced by subsequent "roadmap" for a competitive low-carbon Europe, followed by a "vision" for a competitive and climate neutral economy by 2050. The 2030 framework (cf. section 9.2.3) did outline 2030 targets (an upwards revision of the 2020 targets) but lacked from actual country specific binding targets. While one could argue that after many years working towards 2020 targets, MSs have matured in a sense that they would continue their actions self-determined, and that the given "flexibility" of a community goal is more efficient than national targets, the question remains, why the EU strives to become a world leader in regards to RES, but at the same time does not enforce certain rules.

As to the 2020 targets, the EU is on the best way to achieve them as a whole, with outperforming countries equalising the lower performant MSs in regards to their national targets.

### 14.1.1 Support mechanisms to promote RES

The RED resulted in a manifold landscape of support mechanisms, individually designed and adopted by the Member States. Section 10 is dedicated to this matter.

It can be shown that Feed-in Tariffs (FITs) (fore their simplicity) and quota systems (for their compatibility with liberated markets) were the most commonly adopted promotion schemes in the EU, at least during the first years. Section 10.1 compares the most commonly adopted support instruments and also discusses advantages and disadvantages suggested by the literature.

The FIT tariff is praised as one of the most effective support instruments for RES-E installations, as they provide investors with a low risk and a guarantee for ROI. Also, its simplicity is seen as key to its success. At the same time, poorly designed FITs without degression formulas and revisions are criticised not to be sustainable for long term, as they do not promote efficiency and technical progress. Furthermore, they might shift the financial disadvantage, in case the market price strongly fluctuates. A solution for that are the UK's CfDs, essentially two-sided premium tariffs. With guaranteed selling at a fixed price, feed-in volume can be inefficient or even put high loads on the grid. FIT however has been the preferred choice in the early years of RES-E promotion in the EU.

Quota systems may entail higher policy cost and require more complex design by default, but are regarded as more compatible with the EU electricity market liberalisation strategy and overall are by definition better oriented at the principles of markets than tariff designs. As such, they achieve better competitive prices. In contrast, they may incur higher risk premiums than tariff schemes in case of uncertain development of the electricity price, making them less attractive to investors.

Despite commonalities in regards to applied concepts, the individual design choices of each MS showed substantial differences, as section 10.3 presents. The closer look on each country also reveals that some have completely abolished their support schemes after being in place for only a small number of years. In contrast, others have shown continuous efforts to revise and adapt policies and instruments to actual conditions. Most countries provide support for all types of RES-E, but apply restrictions in terms of capacity.

Some MSs have proven to progressively adapt and evolve their support schemes; it was observed that numerous countries have replaced their FIT schemes with at at least Feed-in Premiums (FIPs), or even quota systems, over the course of time. This kind of development is very positive, considering that in the early stages, experience levels were lower and increased over time. Furthermore, technological advance resulted in RES-E installations becoming competitive and cheaper. The adaptation and revision of promotion schemes is to real conditions is a natural consequence of market and technological advancement, and on the long term prevents abuse of support schemes, which have been originally put in place because of the non-competitiveness.

From today's point of view, support instruments were mostly effective to reach the community 2020 goal of 20% share of Renewables in final energy consumption, but differ from country to country. There has been a significant expansion of RE in the whole EU, after putting in place far more than 1,000 financial and regulatory support measures between 2005 and 2015, strongly pushed by the RED. Overall, each support instrument shows advantages and disadvantages, which may be partly avoided by proper design.

In general, prudent design and layout, and a strategy as to the final objective of a support scheme are they key elements to success and of utmost importance, as well as regular revisions and adaptation to real conditions. Poorly designed support instruments can have negative effects, such as force-shutdown of plants after expiry of support, due to still not operating cost-covering. Examples are biomass plants in Austria, and their currently disputed follow-up tariffs.

Support instruments shall enable technologies while they are not yet competitive, but at the same time be designed in a way the promote and incentivize efficiency and technological advancement. Hence, policy makers must audit their support instruments and align them with strategies, in order to keep up the success rate. From an economic perspective, subsidies in any form are questionable instruments, and to be applied with care; in any case, they shall represent financial aid for a limited time, until independent operation is possible. Otherwise, they risk to impose high cost, which eventually are paid by end consumers.

## 14.2 The role of biomass

Section 11 analyses biomass as RES from different perspectives in order to explain the role, which this material holds in the energy systems of the EU. The general observation is that biomass, among which wood resembles the highest share, has a subordinate role in large-scale applications of energy, and is generally less exploited within the electricity than in the heat sector. Co-firing has been observed toe be a topic of high interest. Barriers to success are the scarcity of feedstock, competing use of land and biomass, sustainability, consequences on land use, biodiversity and water use. A significant contribution requires supporting policies in favour of biomass and on account of conventional fuels.

**Availability and diversity** The inherent diversity of biomass in regards to its different types and materials, properties and spatial distribution are identified as the root causes of hindering exploitation on a larger scale.

From a technological side, materials show large variations in properties and combustion efficiencies, resulting in a manifold landscape of different applications, some more and many less mature. The inhomogeneous nature of feedstock even within a single group of biomass (e.g. wood), such as wood, and its peculiarities lead to difficulties with regards to combustion. This consequently requires sophisticated pre-processing in order to reach homogenous material properties and hence a uniform fuel for conversion units, with low varying efficiencies. Eventually the material properties result in a financial trade-off between pre-processing and efficiency, making it less attractive for investors or even for planning energy systems.

**Alternative use** is an area of conflict specific to biomass, among all other RESs and represents a strong barrier against energy utilization. Opponents argue that agricultural biomass shall be preferably used for food purposes or fodder in animal cultivation, rather than for combustion and energy generation. That is, even energy crops specifically grown for energy purposes are criticised, as they eventually occupy arable land that might be used for alternative purposes. This seems to be a sensible topic especially in countries with lower wealth and prosperity.

**Supply chain** Another identified important aspect is logistics. Given that biomass energy conversion units depend on fuel, they require an effective and efficient supply chain. The supply chain however holds itself a significant cost factor, which is strongly dependent again on material properties, but also on availability, topological conditions and spatial distribution/distances. In short, the supply chains required to operate biomass conversion plants generate significant cost, which increase linearly with the required fuel amount and the transportation distances, but also depend on a large number of other factors. Part I of this thesis was dedicated to this topic, hence it will not be further discussed at this point.

**Carbon neutrality** and the carbon cycle are common concepts in regards to classifying biomass as RES and discussed in section 11.1.2. Some authors even go as far as describing biomass as an indefinite source of RE.

It was shown that literature has different opinions about that topic, and generally agreed that one has to apply those concepts with care. The timeframe in which the carbon cycle is assessed is the most important aspect to consider; the missing equilibrium of human induced GHG emissions and carbon storage in biomass such as forests is reason enough to claim that biomass growing over decades or even centuries shall be treated with care when suggesting its carbon neutrality. The carbon cycle and eventually the carbon neutrality are popular concepts when it comes to promoting biomass for energy utilization.

At the same time, literature disagrees on whether $CO_2$ emissions of wood or other biofuels combustion are actually lower than of conventional fuels. However, even if the carbon cycle were undisputed, it remains questionable whether the combustion of biofuels is the answer to a global strategy of reducing carbon emissions: leaving aside whether emissions of biomass combustion compared to fossil fuels are actually lower or not, emissions still arise from the process and the supply chain.

Notwithstanding conflicting opinions, biomass power and heat plants will have their place in future energy systems, as their feedstock oriented nature provide a constant and on-demand capacity of energy. This makes them fundamentally different to e.g. wind and solar power conversion units which rely on intermittent and volatile resources; and ideal candidates to substitute the remainders of conventional power plants in countries, which are on their way to move away from fossil fuels. Under the aspect of security and quality of supply, constant and on-demand capacity is necessary.

**Potential assessments** are strongly affected by the diversity of biomass too. Section 11.3 presents how they are carried out and which inconsistencies they show. The most important finding is that there is a lack of harmonization in regards to the assessment terms, parameters and definitions, which results in inconsistencies already from the beginning. It is shown that estimated potential figures are strongly diverging, and difficult to compare. Also, authors acknowledge the high uncertainties in their projections.

Assessments of forest areas do not improve the situation, as their results are manifold and largely vary. Literature shows a wide range of publications, with the general consensus that there is no sufficient consensus in terms of harmonized assessment, terms and expressions. This particularly makes large scale planning of forestry based biofuel supply chains and further more energy generation difficult, as the fuel supply data is largely different and may not be compared across countries. (cf. section 11.2.4). Wood is said to be capable of contributing with small to high shares in future energy systems, under different assumptions and scenarios.

Overall, the assessment studies do not provide projections with high certainty, and this observation is emphasized by the fact that they all deviate from each other. Authors agree that successful exploitation of wood, and other types of biofuels, is strongly influenced by policies and societal acceptance.

**Wood for energy purposes** The energy utilization of wood is described as historically relevant and well established by many different authors. Considering forests as a main source of wood for energy generation, similar conflicts arise to the above mentioned, with regards to alternative use. Competing industries may also prevent wood from being efficiently harvested, as well as the commodity price of wood is a driving factor that either favours the energy industry on account of other, wood processing industries, or vice versa. Worldwide, the forests cover approximately a third of the area, with a declining trend however. In contrast, the forest area on the European continent shows an increasing trend.

Section 11.2 assesses the difficulties and barriers of further exploiting wood for energy applications. Among technical and economical barriers, sustainability and ecological concerns are identified as the main barriers. Hindering aspects of technical and economical nature are somewhat similar to those discussed above in general context of biomass. On top, sustainability is a term that was used extensively in literature. Forests are regarded as areas of biodiversity and opponents argue, they must be reserved rather than exhausted for energy. Supporters however argue that the ratio between growth and felling of forests is high enough to preserve forests as they are. It was generally observed that non-tangible values are of major concern when addressing forest management.

## 14.3 Development of energy based on biomass

Statistics show that the EU wide share of Renewables in final energy consumption has increased as a consequence of putting policies in place, leading the EU on track to reach its 2020 goals. Section 12 presents figures from statistical databases to visualize how RES-E evolved over time, with particular focus on biomass. As a general observation, especially in context of biomass, there is sometimes no clear distinction of energy and electricity in statistical databases or even literature.

In terms of support schemes promoting biomass, policies focus less on the electricity sector than on heating and transport. Scientific literature suggests that electricity from biomass is cannot compete with fossil fuels under support regimes of short eligibility periods (which range up to 25 years). Analysis of the MSs adopted policies show that few have evidently put focus on biomass. Not all countries have provided technology specific targets, but the range of projected biomass share according to the NREAPs is large, which lets assume that those figures may not be reliable. While policies are mostly technology neutral, some countries do implement instruments in favour of biomass, whereas others do the opposite. No consistency can be observed, however this may be explained with different spatial distributions of biomass supply.

In the general increase of RES, statistics indicate that solid biofuels including wood have experienced the strongest gains in the EU in terms of primary energy production and inland energy consumption. As to the gross generation of electricity however, biofuels clearly did not manage to compete with wind energy, notwithstanding the fact that its share also increased for the last two decades. Biomass represents a share of approximately 16% of the gross electricity production from Renewables by 2016, which in turn represents approximately 5% of the overall production (including fossil). Those results emphasize wood and other biofuels indeed represent important sources for energy, however the question remains whether the trend of the past decade continues; clearly, revised policies will be required in order to reach that.

## 14.4 Biomass in Austria

The final section puts the spotlight on the Republic of Austria (cf. section 13). Austria has comparably high RES targets (34% share of total energy consumption and over 70% share of final electricity consumption). The Green Electricity Act (OeSG) in consequence of the RED has established a support framework consisting mainly of fixed FITs to promote RES-E. As a result, installed capacity of eligible RES-E installations has more than doubled. Today, the share of RES-E is remarkably high, differs however depending on perspective: the share of Renewables in final electricity consumption was as high as 84% in 2017, out of which 7% came from biomass. In terms of gross electricity production, RESs represent a share of approximately 75%, 6.4% of the overall production coming from biomass. It appears that electricity from biomass is not exported.

Notwithstanding the positive effects and success of the OeSG, the fact that no major revisions were applied since the beginnings is a point of criticism: the FIT does not incentivise efficiency and technological advancement, and is far from market oriented, without any degression schemes. The consequences become visible in particular for biomass power plants, which appear to be threatened once their support expires. Recently (2019), the government intended to “save” those installations with an amendment of the OeSG, providing successive rates to plants, of which the support is about to or already expired. At the time this work was finalized, political opponents were about to block this amendment due to lack of transparency.

Austria has set itself the brave target of generating 100% of the inland electricity from Renewables in its “Mission 2030”. Biomass today has a comparably low contribution to electricity production today, and is majorly used for CHP plants. Projections suggest however that under fostering conditions, existing resources would allow to increase the share of RES-E from biomass by 48%. In order to reach the 100% target, the promotion of efficient biomass power plants are regarded as essential, also in terms of security of supply. However, the necessary actions are not transposed into law yet. Critics claim that the existing framework will not be sufficient to reach it.

## 14.5 Overall conclusions

Among the Renewable Energy Sources, biomass stands out with clear technical advantages (constant and on-demand provision of energy) but a high number of disadvantages that can be summed up as being not cost competitive. The diversity of feedstock leads to technical challenges (efficiency) and high supply chain costs, which eventually make biomass operated plants less applicable for large-scale applications. An additional barrier is the scarcity of feedstock, impact on land use and conflicts with alternative use. This is valid of any kind of growing biomass such as energy crops and wood. Forest areas have a large number of stakeholders, making the large scale utilization of wood even more difficult (sustainability, biodiversity).

Emissions and carbon neutrality are a strong promotional factor for bioenergy, however they are subject to opposing opinions too, as their conversion processes still emit carbon and other GHGs, fine dust and other particular matter, even if the carbon is considered neutral. While it is acknowledged that biomass plays an important role in abolishment of fossil and nuclear power, the prices of energy production with comparable efficiencies are still too high, and it remains questionable whether support policies will suffice to change that. Some say that biomass electricity with its high prices can be still competitive, provided that the price of carbon is increased, as this would penalize fossil fuels mainly.

Efficient and low-cost supply chain cost are required to install large scale conversion plants. Additionally an open-mindedness of forestry and agricultural sectors stakeholders. Otherwise, biomass will remain important only in regional energy systems, with decentralized CHP conversion plants.

On the path to maintaining or reducing GHG emissions, biomass is not the single answer, but it plays an undisputed role in the mix of RESs. The uncertainties connected with biomass make long-term predictions impossible In light of other sectors than electricity, such as transport and buildings, the demand for electricity will continue to rise.

It is suggested that only more efficient technologies with less emissions, an increase of carbon prices, and all that combined with supporting policy frameworks on account of conventional energy, will make biomass a viable source of energy. As long as conventional power plants exist and feed energy into the European grid, the pan-European electricity market will not be able to provide conditions which favour RES-E. Austria may represent only a fraction of the EU. But the development of RES-E and their support frameworks, and especially the recent political conflicts around the Green Electricity Act Amendment show that the topic is of large complexity. This lets assume that all other MSs may deal with similar problems and challenges, leading to the question whether the solution is a common binding strategy including progressive abolishment of conventional power plants.

In order to assess the future of biomass in the EU, a solution may be to start with a harmonized potential assessment in all MSs on a fine spatial distribution. This baseline could be furthermore used to design a pan-European distribution of decentralized power plants of similar types, standardized supply chains and potentially a top level supply chain and market for biomass commodities.

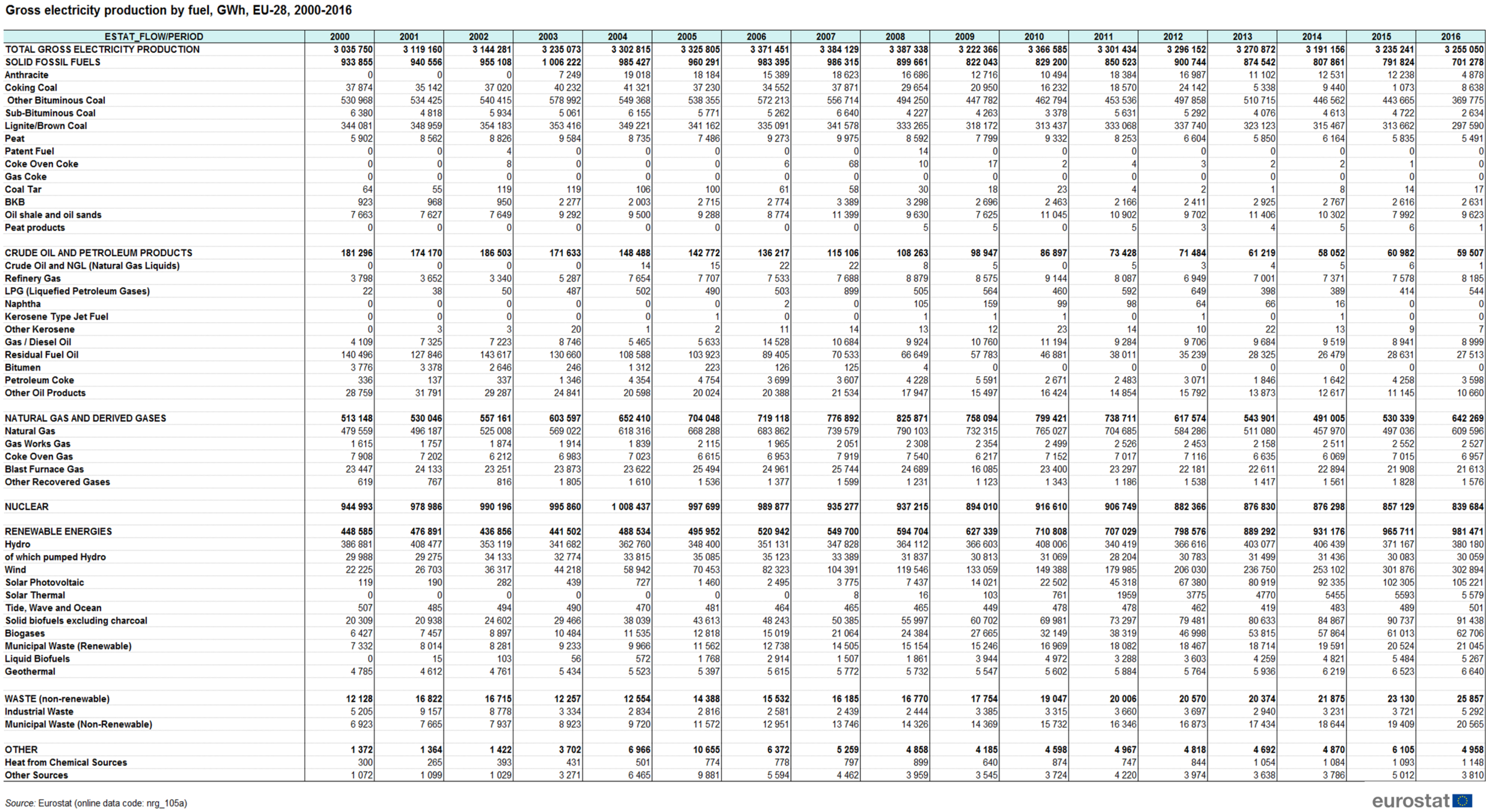
# Appendices

Table 17: Table of quantified emission limitation or reduction commitments for the purpose of determining the respective emission levels allocated to the European Community and its Member States in accordance with article 4 of the Kyoto Protocol (from: Council of the European Union (2002) Annex II)

| | Quantified emission reduction commitment as laid down in Annex B of the Kyoto Protocol (percentage of base year or period) |
|---|---|
| **European Community** | **92%** |
| | Quantified emission limitation or reduction commitment as agreed in accordance with article 4(1) of the Kyoto Protocol (percentage of base year or period) |
| Belgium | 92.50% |
| Denmark | 79% |
| Germany | 79% |
| Greece | 125% |
| Spain | 115% |
| France | 100% |
| Ireland | 113% |
| Italy | 93.50% |
| Luxembourg | 72% |
| Netherlands | 94% |
| Austria | 87% |
| Portugal | 127% |
| Finland | 100% |
| Sweden | 104% |
| United Kingdom | 87.50% |

Table 18: National overall targets for the share of energy from renewable sources in gross final consumption of energy in 2020 (Council of the European Union and European Parliament, 2009b)

| | Share of energy from renewable sources in gross final consumption of energy, 2005 (S2005) | Target for share of energy from renewable sources in gross final consumption of energy, 2020 (S2020) |
|---|---|---|
| Belgium | 2,2 % | 13 % |
| Bulgaria | 9,4 % | 16 % |
| Czech Republic | 6,1 % | 13 % |
| Denmark | 17,0 % | 30 % |
| Germany | 5,8 % | 18 % |
| Estonia | 18,0 % | 25 % |
| Ireland | 3,1 % | 16 % |
| Greece | 6,9 % | 18 % |
| Spain | 8,7 % | 20 % |
| France | 10,3 % | 23 % |
| Italy | 5,2 % | 17 % |
| Cyprus | 2,9 % | 13 % |
| Latvia | 32,6 % | 40 % |
| Lithuania | 15,0 % | 23 % |
| Luxembourg | 0,9 % | 11 % |
| Hungary | 4,3 % | 13 % |
| Malta | 0,0 % | 10 % |
| Netherlands | 2,4 % | 14 % |
| Austria | 23,3 % | 34 % |
| Poland | 7,2 % | 15 % |
| Portugal | 20,5 % | 31 % |
| Romania | 17,8 % | 24 % |
| Slovenia | 16,0 % | 25 % |
| Slovak Republic | 6,7 % | 14 % |
| Finland | 28,5 % | 38 % |
| Sweden | 39,8 % | 49 % |
| United Kingdom | 1,3 % | 15 % |

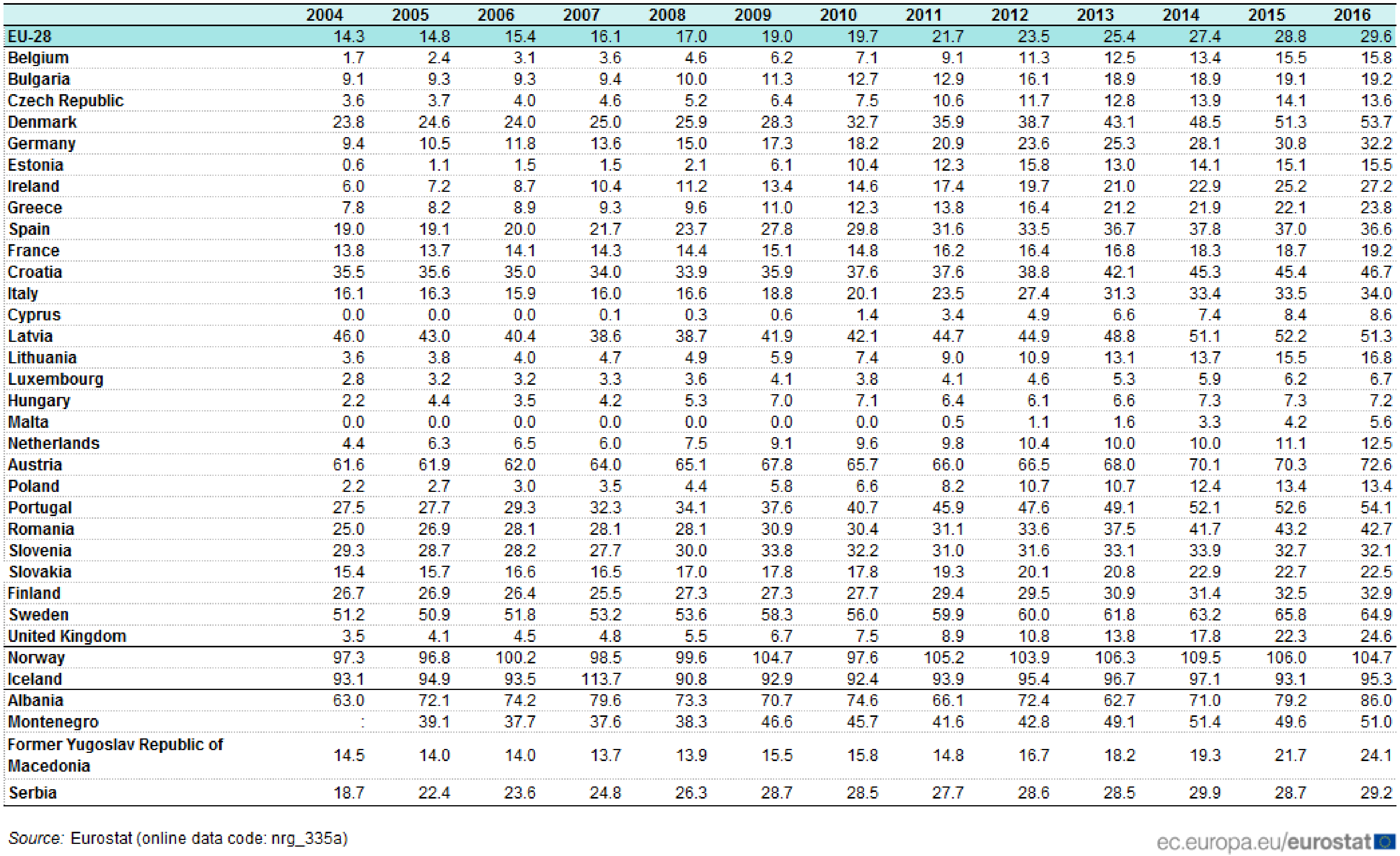


Gross electricity production by fuel, GWh, EU-28, 2000-2016

| ESTAT_FLOW/PERIOD | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **TOTAL GROSS ELECTRICITY PRODUCTION** | **3 035 750** | **3 119 160** | **3 144 281** | **3 235 073** | **3 302 815** | **3 325 805** | **3 371 451** | **3 384 129** | **3 387 338** | **3 222 366** | **3 366 585** | **3 301 434** | **3 296 152** | **3 270 872** | **3 191 156** | **3 235 241** | **3 255 050** |
| **SOLID FOSSIL FUELS** | **933 855** | **940 556** | **955 108** | **1 006 222** | **985 427** | **960 291** | **983 395** | **986 315** | **899 661** | **822 043** | **829 200** | **850 523** | **900 744** | **874 542** | **807 861** | **791 824** | **701 278** |
| Anthracite | 0 | 0 | 0 | 7 249 | 19 018 | 18 184 | 15 389 | 18 623 | 16 686 | 12 716 | 10 494 | 18 384 | 16 987 | 11 102 | 12 531 | 12 238 | 4 878 |
| Coking Coal | 37 874 | 35 142 | 37 020 | 40 232 | 41 321 | 37 230 | 34 552 | 37 871 | 29 654 | 20 950 | 16 232 | 18 570 | 24 142 | 5 338 | 9 440 | 1 073 | 8 638 |
| Other Bituminous Coal | 530 968 | 534 425 | 540 415 | 578 992 | 549 368 | 538 355 | 572 213 | 556 714 | 494 250 | 447 782 | 462 794 | 453 536 | 497 858 | 510 715 | 446 562 | 443 665 | 369 775 |
| Sub-Bituminous Coal | 6 380 | 4 818 | 5 934 | 5 061 | 6 155 | 5 771 | 5 262 | 6 640 | 4 227 | 4 263 | 3 378 | 5 631 | 5 292 | 4 076 | 4 613 | 4 722 | 2 634 |
| Lignite/Brown Coal | 344 081 | 348 959 | 354 183 | 353 416 | 349 221 | 341 162 | 335 091 | 341 578 | 333 265 | 318 172 | 313 437 | 333 068 | 337 740 | 323 123 | 315 467 | 313 662 | 297 590 |
| Peat | 5 902 | 8 562 | 8 826 | 9 584 | 8 735 | 7 486 | 9 273 | 9 975 | 8 592 | 7 799 | 9 332 | 8 253 | 6 604 | 5 850 | 6 164 | 5 835 | 5 491 |
| Patent Fuel | 0 | 0 | 4 | 0 | 0 | 0 | 0 | 0 | 14 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Coke Oven Coke | 0 | 0 | 8 | 0 | 0 | 0 | 6 | 68 | 10 | 17 | 2 | 4 | 3 | 2 | 2 | 1 | 0 |
| Gas Coke | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Coal Tar | 64 | 55 | 119 | 119 | 106 | 100 | 61 | 58 | 30 | 18 | 23 | 4 | 2 | 1 | 8 | 14 | 17 |
| BKB | 923 | 968 | 950 | 2 277 | 2 003 | 2 715 | 2 774 | 3 389 | 3 298 | 2 696 | 2 463 | 2 166 | 2 411 | 2 925 | 2 767 | 2 616 | 2 631 |
| Oil shale and oil sands | 7 663 | 7 627 | 7 649 | 9 292 | 9 500 | 9 288 | 8 774 | 11 399 | 9 630 | 7 625 | 11 045 | 10 902 | 9 702 | 11 406 | 10 302 | 7 992 | 9 623 |
| Peat products | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 5 | 0 | 5 | 3 | 4 | 5 | 6 | 1 |
| | | | | | | | | | | | | | | | | | |
| **CRUDE OIL AND PETROLEUM PRODUCTS** | **181 296** | **174 170** | **186 503** | **171 633** | **148 488** | **142 772** | **136 217** | **115 106** | **108 263** | **98 947** | **86 897** | **73 428** | **71 484** | **61 219** | **58 052** | **60 982** | **59 507** |
| Crude Oil and NGL (Natural Gas Liquids) | 0 | 0 | 0 | 0 | 14 | 15 | 22 | 22 | 8 | 5 | 0 | 5 | 3 | 4 | 5 | 6 | 1 |
| Refinery Gas | 3 798 | 3 652 | 3 340 | 5 287 | 7 654 | 7 707 | 7 533 | 7 688 | 8 879 | 8 575 | 9 144 | 8 087 | 6 949 | 7 001 | 7 371 | 7 578 | 8 185 |
| LPG (Liquefied Petroleum Gases) | 22 | 38 | 50 | 487 | 502 | 490 | 503 | 899 | 505 | 564 | 460 | 592 | 649 | 398 | 389 | 414 | 544 |
| Naphtha | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 105 | 159 | 99 | 98 | 64 | 66 | 16 | 0 | 0 |
| Kerosene Type Jet Fuel | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 0 | 0 |
| Other Kerosene | 0 | 3 | 3 | 20 | 1 | 2 | 11 | 14 | 13 | 12 | 23 | 14 | 10 | 22 | 13 | 9 | 7 |
| Gas / Diesel Oil | 4 109 | 7 325 | 7 223 | 8 746 | 5 465 | 5 633 | 14 528 | 10 684 | 9 924 | 10 760 | 11 194 | 9 284 | 9 706 | 9 684 | 9 519 | 8 941 | 8 999 |
| Residual Fuel Oil | 140 496 | 127 846 | 143 617 | 130 660 | 108 588 | 103 923 | 89 405 | 70 533 | 66 649 | 57 783 | 46 881 | 38 011 | 35 239 | 28 325 | 26 479 | 28 631 | 27 513 |
| Bitumen | 3 776 | 3 378 | 2 646 | 246 | 1 312 | 223 | 126 | 125 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Petroleum Coke | 336 | 137 | 337 | 1 346 | 4 354 | 4 754 | 3 699 | 3 607 | 4 228 | 5 591 | 2 671 | 2 483 | 3 071 | 1 846 | 1 642 | 4 258 | 3 598 |
| Other Oil Products | 28 759 | 31 791 | 29 287 | 24 841 | 20 598 | 20 024 | 20 388 | 21 534 | 17 947 | 15 497 | 16 424 | 14 854 | 15 792 | 13 873 | 12 617 | 11 145 | 10 660 |
| | | | | | | | | | | | | | | | | | |
| **NATURAL GAS AND DERIVED GASES** | **513 148** | **530 046** | **557 161** | **603 597** | **652 410** | **704 048** | **719 118** | **776 892** | **825 871** | **758 094** | **799 421** | **738 711** | **617 574** | **543 901** | **491 005** | **530 339** | **642 269** |
| Natural Gas | 479 559 | 496 187 | 525 008 | 569 022 | 618 316 | 668 288 | 683 862 | 739 579 | 790 103 | 732 315 | 765 027 | 704 685 | 584 286 | 511 080 | 457 970 | 497 036 | 609 596 |
| Gas Works Gas | 1 615 | 1 757 | 1 874 | 1 914 | 1 839 | 2 115 | 1 965 | 2 051 | 2 308 | 2 354 | 2 499 | 2 526 | 2 453 | 2 158 | 2 511 | 2 552 | 2 527 |
| Coke Oven Gas | 7 908 | 7 202 | 6 212 | 6 983 | 7 023 | 6 615 | 6 953 | 7 919 | 7 540 | 6 217 | 7 152 | 7 017 | 7 116 | 6 635 | 6 069 | 7 015 | 6 957 |
| Blast Furnace Gas | 23 447 | 24 133 | 23 251 | 23 873 | 23 622 | 25 494 | 24 961 | 25 744 | 24 689 | 16 085 | 23 400 | 23 297 | 22 181 | 22 611 | 22 894 | 21 908 | 21 613 |
| Other Recovered Gases | 619 | 767 | 816 | 1 805 | 1 610 | 1 536 | 1 377 | 1 599 | 1 231 | 1 123 | 1 343 | 1 186 | 1 538 | 1 417 | 1 561 | 1 828 | 1 576 |
| | | | | | | | | | | | | | | | | | |
| **NUCLEAR** | **944 993** | **978 986** | **990 196** | **995 860** | **1 008 437** | **997 699** | **989 877** | **935 277** | **937 215** | **894 010** | **916 610** | **906 749** | **882 366** | **876 830** | **876 298** | **857 129** | **839 684** |
| | | | | | | | | | | | | | | | | | |
| **RENEWABLE ENERGIES** | **448 585** | **476 891** | **436 856** | **441 502** | **488 534** | **495 952** | **520 942** | **549 700** | **594 704** | **627 339** | **710 808** | **707 029** | **798 576** | **889 292** | **931 176** | **965 711** | **981 471** |
| Hydro | 386 881 | 408 477 | 353 119 | 341 682 | 362 760 | 348 400 | 351 131 | 347 828 | 364 112 | 366 603 | 408 006 | 340 419 | 366 616 | 403 077 | 406 439 | 371 167 | 380 180 |
| of which pumped Hydro | 29 988 | 29 275 | 34 133 | 32 774 | 33 815 | 35 085 | 35 123 | 33 389 | 31 837 | 30 813 | 31 069 | 28 204 | 30 783 | 31 499 | 31 436 | 30 083 | 30 059 |
| Wind | 22 225 | 26 703 | 36 317 | 44 218 | 58 942 | 70 453 | 82 323 | 104 391 | 119 546 | 133 059 | 149 388 | 179 985 | 206 030 | 236 750 | 253 102 | 301 876 | 302 894 |
| Solar Photovoltaic | 119 | 190 | 282 | 439 | 727 | 1 460 | 2 495 | 3 775 | 7 437 | 14 021 | 22 502 | 45 318 | 67 380 | 80 919 | 92 335 | 102 305 | 105 221 |
| Solar Thermal | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 8 | 16 | 103 | 761 | 1959 | 3775 | 4770 | 5455 | 5593 | 5 579 |
| Tide, Wave and Ocean | 507 | 485 | 494 | 490 | 470 | 481 | 464 | 465 | 465 | 449 | 478 | 478 | 462 | 419 | 483 | 489 | 501 |
| Solid biofuels excluding charcoal | 20 309 | 20 938 | 24 602 | 29 466 | 38 039 | 43 613 | 48 243 | 50 385 | 55 997 | 60 702 | 69 981 | 73 297 | 79 481 | 80 633 | 84 867 | 90 737 | 91 438 |
| Biogases | 6 427 | 7 457 | 8 897 | 10 484 | 11 535 | 12 818 | 15 019 | 21 064 | 24 384 | 27 665 | 32 149 | 38 319 | 46 998 | 53 815 | 57 864 | 61 013 | 62 706 |
| Municipal Waste (Renewable) | 7 332 | 8 014 | 8 281 | 9 233 | 9 966 | 11 562 | 12 738 | 14 505 | 15 154 | 15 246 | 16 969 | 18 082 | 18 467 | 18 714 | 19 591 | 20 524 | 21 045 |
| Liquid Biofuels | 0 | 15 | 103 | 56 | 572 | 1 768 | 2 914 | 1 507 | 1 861 | 3 944 | 4 972 | 3 288 | 3 603 | 4 259 | 4 821 | 5 484 | 5 267 |
| Geothermal | 4 785 | 4 612 | 4 761 | 5 434 | 5 523 | 5 397 | 5 615 | 5 772 | 5 732 | 5 547 | 5 602 | 5 884 | 5 764 | 5 936 | 6 219 | 6 523 | 6 640 |
| | | | | | | | | | | | | | | | | | |
| **WASTE (non-renewable)** | **12 128** | **16 822** | **16 715** | **12 257** | **12 554** | **14 388** | **15 532** | **16 185** | **16 770** | **17 754** | **19 047** | **20 006** | **20 570** | **20 374** | **21 875** | **23 130** | **25 857** |
| Industrial Waste | 5 205 | 9 157 | 8 778 | 3 334 | 2 834 | 2 816 | 2 581 | 2 439 | 2 444 | 3 385 | 3 315 | 3 660 | 3 697 | 2 940 | 3 231 | 3 721 | 5 292 |
| Municipal Waste (Non-Renewable) | 6 923 | 7 665 | 7 937 | 8 923 | 9 720 | 11 572 | 12 951 | 13 746 | 14 326 | 14 369 | 15 732 | 16 346 | 16 873 | 17 434 | 18 644 | 19 409 | 20 565 |
| | | | | | | | | | | | | | | | | | |
| **OTHER** | **1 372** | **1 364** | **1 422** | **3 702** | **6 966** | **10 655** | **6 372** | **5 259** | **4 858** | **4 185** | **4 598** | **4 967** | **4 818** | **4 692** | **4 870** | **6 105** | **4 958** |
| Heat from Chemical Sources | 300 | 265 | 393 | 431 | 501 | 774 | 778 | 797 | 899 | 640 | 874 | 747 | 844 | 1 054 | 1 084 | 1 093 | 1 148 |
| Other Sources | 1 072 | 1 099 | 1 029 | 3 271 | 6 465 | 9 881 | 5 594 | 4 462 | 3 959 | 3 545 | 3 724 | 4 220 | 3 974 | 3 638 | 3 786 | 5 012 | 3 810 |

*Source:* Eurostat (online data code: nrg_105a)

Table 19: Gross electricity generation by fuel in GWh, EU-28, 2000-2016



| | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| EU-28 | 14.3 | 14.8 | 15.4 | 16.1 | 17.0 | 19.0 | 19.7 | 21.7 | 23.5 | 25.4 | 27.4 | 28.8 | 29.6 |
| Belgium | 1.7 | 2.4 | 3.1 | 3.6 | 4.6 | 6.2 | 7.1 | 9.1 | 11.3 | 12.5 | 13.4 | 15.5 | 15.8 |
| Bulgaria | 9.1 | 9.3 | 9.3 | 9.4 | 10.0 | 11.3 | 12.7 | 12.9 | 16.1 | 18.9 | 18.9 | 19.1 | 19.2 |
| Czech Republic | 3.6 | 3.7 | 4.0 | 4.6 | 5.2 | 6.4 | 7.5 | 10.6 | 11.7 | 12.8 | 13.9 | 14.1 | 13.6 |
| Denmark | 23.8 | 24.6 | 24.0 | 25.0 | 25.9 | 28.3 | 32.7 | 35.9 | 38.7 | 43.1 | 48.5 | 51.3 | 53.7 |
| Germany | 9.4 | 10.5 | 11.8 | 13.6 | 15.0 | 17.3 | 18.2 | 20.9 | 23.6 | 25.3 | 28.1 | 30.8 | 32.2 |
| Estonia | 0.6 | 1.1 | 1.5 | 1.5 | 2.1 | 6.1 | 10.4 | 12.3 | 15.8 | 13.0 | 14.1 | 15.1 | 15.5 |
| Ireland | 6.0 | 7.2 | 8.7 | 10.4 | 11.2 | 13.4 | 14.6 | 17.4 | 19.7 | 21.0 | 22.9 | 25.2 | 27.2 |
| Greece | 7.8 | 8.2 | 8.9 | 9.3 | 9.6 | 11.0 | 12.3 | 13.8 | 16.4 | 21.2 | 21.9 | 22.1 | 23.8 |
| Spain | 19.0 | 19.1 | 20.0 | 21.7 | 23.7 | 27.8 | 29.8 | 31.6 | 33.5 | 36.7 | 37.8 | 37.0 | 36.6 |
| France | 13.8 | 13.7 | 14.1 | 14.3 | 14.4 | 15.1 | 14.8 | 16.2 | 16.4 | 16.8 | 18.3 | 18.7 | 19.2 |
| Croatia | 35.5 | 35.6 | 35.0 | 34.0 | 33.9 | 35.9 | 37.6 | 37.6 | 38.8 | 42.1 | 45.3 | 45.4 | 46.7 |
| Italy | 16.1 | 16.3 | 15.9 | 16.0 | 16.6 | 18.8 | 20.1 | 23.5 | 27.4 | 31.3 | 33.4 | 33.5 | 34.0 |
| Cyprus | 0.0 | 0.0 | 0.0 | 0.1 | 0.3 | 0.6 | 1.4 | 3.4 | 4.9 | 6.6 | 7.4 | 8.4 | 8.6 |
| Latvia | 46.0 | 43.0 | 40.4 | 38.6 | 38.7 | 41.9 | 42.1 | 44.7 | 44.9 | 48.8 | 51.1 | 52.2 | 51.3 |
| Lithuania | 3.6 | 3.8 | 4.0 | 4.7 | 4.9 | 5.9 | 7.4 | 9.0 | 10.9 | 13.1 | 13.7 | 15.5 | 16.8 |
| Luxembourg | 2.8 | 3.2 | 3.2 | 3.3 | 3.6 | 4.1 | 3.8 | 4.1 | 4.6 | 5.3 | 5.9 | 6.2 | 6.7 |
| Hungary | 2.2 | 4.4 | 3.5 | 4.2 | 5.3 | 7.0 | 7.1 | 6.4 | 6.1 | 6.6 | 7.3 | 7.3 | 7.2 |
| Malta | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.5 | 1.1 | 1.6 | 3.3 | 4.2 | 5.6 |
| Netherlands | 4.4 | 6.3 | 6.5 | 6.0 | 7.5 | 9.1 | 9.6 | 9.8 | 10.4 | 10.0 | 10.0 | 11.1 | 12.5 |
| Austria | 61.6 | 61.9 | 62.0 | 64.0 | 65.1 | 67.8 | 65.7 | 66.0 | 66.5 | 68.0 | 70.1 | 70.3 | 72.6 |
| Poland | 2.2 | 2.7 | 3.0 | 3.5 | 4.4 | 5.8 | 6.6 | 8.2 | 10.7 | 10.7 | 12.4 | 13.4 | 13.4 |
| Portugal | 27.5 | 27.7 | 29.3 | 32.3 | 34.1 | 37.6 | 40.7 | 45.9 | 47.6 | 49.1 | 52.1 | 52.6 | 54.1 |
| Romania | 25.0 | 26.9 | 28.1 | 28.1 | 28.1 | 30.9 | 30.4 | 31.1 | 33.6 | 37.5 | 41.7 | 43.2 | 42.7 |
| Slovenia | 29.3 | 28.7 | 28.2 | 27.7 | 30.0 | 33.8 | 32.2 | 31.0 | 31.6 | 33.1 | 33.9 | 32.7 | 32.1 |
| Slovakia | 15.4 | 15.7 | 16.6 | 16.5 | 17.0 | 17.8 | 17.8 | 19.3 | 20.1 | 20.8 | 22.9 | 22.7 | 22.5 |
| Finland | 26.7 | 26.9 | 26.4 | 25.5 | 27.3 | 27.3 | 27.7 | 29.4 | 29.5 | 30.9 | 31.4 | 32.5 | 32.9 |
| Sweden | 51.2 | 50.9 | 51.8 | 53.2 | 53.6 | 58.3 | 56.0 | 59.9 | 60.0 | 61.8 | 63.2 | 65.8 | 64.9 |
| United Kingdom | 3.5 | 4.1 | 4.5 | 4.8 | 5.5 | 6.7 | 7.5 | 8.9 | 10.8 | 13.8 | 17.8 | 22.3 | 24.6 |
| Norway | 97.3 | 96.8 | 100.2 | 98.5 | 99.6 | 104.7 | 97.6 | 105.2 | 103.9 | 106.3 | 109.5 | 106.0 | 104.7 |
| Iceland | 93.1 | 94.9 | 93.5 | 113.7 | 90.8 | 92.9 | 92.4 | 93.9 | 95.4 | 96.7 | 97.1 | 93.1 | 95.3 |
| Albania | 63.0 | 72.1 | 74.2 | 79.6 | 73.3 | 70.7 | 74.6 | 66.1 | 72.4 | 62.7 | 71.0 | 79.2 | 86.0 |
| Montenegro | : | 39.1 | 37.7 | 37.6 | 38.3 | 46.6 | 45.7 | 41.6 | 42.8 | 49.1 | 51.4 | 49.6 | 51.0 |
| Former Yugoslav Republic of Macedonia | 14.5 | 14.0 | 14.0 | 13.7 | 13.9 | 15.5 | 15.8 | 14.8 | 16.7 | 18.2 | 19.3 | 21.7 | 24.1 |
| Serbia | 18.7 | 22.4 | 23.6 | 24.8 | 26.3 | 28.7 | 28.5 | 27.7 | 28.6 | 28.5 | 29.9 | 28.7 | 29.2 |

*Source:* Eurostat (online data code: nrg_335a)

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Table 20: Share of electricity from renewable sources in gross electricity consumption, EU-28, 2004-2016 (source: EUROSTAT, online data code nrg 335a)

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