Optimal Allocation and Capacity of Renewable Energies, Storage Systems and Transmission Grid in the Future European Power System

Ing. Civil Ricardo Alvarez, IAEW RWTH Aachen University, Germany.
Dipl.-Ing Tjark Thien, PGS E.ON ERC, RWTH Aachen University, Germany.
BSc. Melchior Moos, PGS E.ON ERC, RWTH Aachen University, Germany.
MSc. Hengsi Chen, IAEW RWTH Aachen University, Germany.
MSc. Zhuang Cai, PGS E.ON ERC, RWTH Aachen University, Germany.
Dr. rer. nat. Matthias Leuthold, PGS E.ON ERC, RWTH Aachen University, Germany.
Univ.-Prof. Dr.-Ing. Uwe Sauer, PGS E.ON ERC, RWTH Aachen University, Germany.
Univ.-Prof. Dr.-Ing. Albert Moser, IAEW RWTH Aachen University, Germany.

Abstract

The reduction of the greenhouse gas emission to 80-95% below 1990 levels by 2050 adopted by the European Commission in the “Energy Roadmap 2050” brings the need of assessing and evaluating different options to achieve that goal. Among them, one major challenge is to transform the current European Power System towards a one with a higher share of renewable energies. As a consequence, questions like optimal allocation and capacity of renewable energy sources (RES) and storage systems in Europe, as well as the transmission grid between European regions naturally arises. In order to approach those questions, an optimization tool called Genesys (Genetic Optimization of a European Energy System) was developed. Genesys optimizes the capacity and allocation of RES, the storage system and transmission network in order to get minimal overall economic costs. Exemplary results for the EUMENA Region (Europe, Middle East and North Africa) for the year 2050 show an optimal installed capacity of RES of 5,261 GW, a HVDC overlay grid between the regions of 1,318,268 GWkm, and a storage capacity of 756 TWh. Such a system would lead to total generation costs of 8.06 ct/kWh. The development of Genesys was promoted by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), within the project code FKZ: 0325366.

1 Introduction

In the Communication “Energy Roadmap 2050” the European Commission announced its commitment to reduce the greenhouse gas emissions to 80-95% below 1990 levels by 2050 [1]. Such a strong reduction of greenhouse gas emissions can only be achieved by transforming the current power system to a one with high shares of renewable energy sources (RES), such as wind and solar power. Consequently, the German Government aims to achieve 80% of RES in the electricity supply sector in the year 2050 [2]. Due to the intermittent nature of generation based on RES, a continuous supply in a system with high shares of these types of technologies can only be achieved with proper storage and transmission system.

In order to contribute finding an optimal European Power System that meets the high shares of RES requirements, an optimization tool called Genesys (Genetic Optimization of a European Energy System) was developed. Genesys optimizes the capacity and allocation of RES, the storage system and transmission network in order to get minimal overall economic costs.

The optimization process combines a covariance matrix adaptation evolution strategy (CMA-ES), which generates candidate solutions, with a time-step simulation based on a Hierarchical System Management (HSM), which simulates the power system operation of each candidate and calculate its operating costs. The input data as well as the optimization parameters can be given either in a database or in CSV files.

In order to compare the performance of the HSM, an optimal operation of the power system based on a LP Formulation and solved with CPLEX is implemented. Analogically, the complete system optimization (capacity and operation) can be solved with CPLEX based on its LP Formulation, which enables to compare the performance of the obtained solution with the combination of CMA-ES and the HSM approach. To provide a graphical view of the optimal power system and its operation, simulated either with HSM or with CPLEX, a visualization tool is also implemented. Genesys is free software that can be redistributed and/or modified.

The Genesys Project includes a homepage, where all input data, assumed technical and economical parameters, related literature, as well as the optimization tool can be found and downloaded free of charge. The homepage also contains a forum, where researchers in the field can give their input, compare results and contribute to the further development of Genesys.

The objective of this contribution is to present the optimization tool Genesys. Chapter 2 shows a description of the main features of Genesys. Chapter 3 shows exemplary results obtained with Genesys for the EUMENA Region (Europe, Middle East and North Africa) in the year 2050.

2 Optimization Tool Genesys

2.1 Power System Modelling

2.1.1 Input data

In Genesys, a power system is modelled in regions, where each region is represented as a node. This means that the load, the weather data and the generation and storage

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units are aggregated within a region. Cross-border transmission lines between two regions are also summarized to one aggregated connection with its maximal power transfer capacity.

Input data of Genesys are the regions and the distance between them, the technical and economical parameters of the generation, storage and transmission technologies to be considered, the annual demand and its profile in each region, and the generation profile of non dispatchable units such as RES. In order to consider the storage need, which arises from the intermittent generation of RES and depends on weather and load extremes, several years of hourly time series of the load and the weather data can be considered for the optimization and power system simulation.

2.1.2 Generation system

The generation system is aggregated in each region according to generation technologies. Therefore, each region contains only the installed capacity of each generation technology being considered. Generation technologies are described by

- the physical form of input and output (electricity, water, solar radiation, etc.)
- dispatchability (plus time series generation if not dispatchable)
- its installation costs (€/kW)
- the operation and maintenance rate (as a %/year of the installation costs)
- its interest rate (%/year)
- the lifetime (years)
- its fuel independent generation costs (€/kWh)
- its generation efficiency η (%)
- if it is a storage charger (SC) or storage discharger (SD)

Generators in Genesys can be power plants, which produce electricity from primary energy, storage dischargers, which produce electricity from storages while lowering the state of charge, and storage chargers, which take electricity to charge storages while increasing the state of charge. Generation technologies which produce electricity from primary resources can have fuel costs (in case of conventional power plants) or not (in case of RES).

2.1.3 Transmission system

The transmission lines between regions are also aggregated to one connection and therefore only its total transmission capacity is modelled. Each transmission technology is described by

- the installation costs of the line (€/(100km*kW))
- the installation costs of the converter station for HVDC lines (€/kW)
- the lifetime (years)

Transmission lines are assumed to be fully controllable in terms of power flow.

2.1.4 Storage system

Genesys uses a simple approach to model storage systems. Just like other power system components, all storages are aggregated within a region according to the storage technology, thus only accounting for its total storage capacity. Storage technologies are described by

- the charging and discharging efficiencies (η_{SC} and η_{SD} respectively) in (%)
- the installation costs of storage capacity (€/kWh)
- interest rate (%/year)
- operation and maintenance (as a %/year of the installation costs)
- storage unit
- and the lifetime (years)

The energy balance of the storages E_{st} between two consecutive periods t_n and t_{n+1} is showed in equation (1).

$$\frac{E_{st}(t_{n+1}) - E_{st}(t_n)}{t_{n+1} - t_n} = \eta_{sc} P_{sc}(t_n) + \frac{1}{\eta_{sd}} P_{sd}(t_n) \qquad (1)$$

2.2 Power System Optimization: Covariance Matrix Adaptation Evolution Strategy (CMA-ES)

The optimization of the power system is based on a covariance matrix adaption evolution strategy (CMA-ES) [3]. Using an evolution strategy allows the use of non-linear objective functions, which is an important feature in order to model the non-linear characteristics, for example of storages. Evolution strategies also enable easy parallelization of the power system optimization algorithm.

Possible power system candidates are represented by individuals and a set of individuals represent a population. Each individual consists of genes which correspond to the system utility's power and capacity ratings. The performance of each individual is represented by its fitness value, which is quantified by means of an objective function. In this case, the objective function is to minimize the total cost of the system (annuity of installation costs, maintenance and operating costs).

The evolution process begins with a start generation of individuals, which are created randomly. Next, the fitness value of each individual is calculated by means of a time-step simulation of the power system based on defined hierarchical rules (HSM), as described in chapter 2.3.

After the evaluation of all individuals, a selection process is carried on by calculating a new mean value m for the mutation with the covariance matrix. The new mean value is calculated from a weighted average of the best candidate solutions based on their fitness ranking. After this step, the adaption of the covariance matrix C^T is carried out based on the successfulness of previous mutation steps. During the process, the variance of each gene is adapted in such a way that parameters that improve the fitness when changed to always the same direction get a larger variance parameter. In the last step, the next solution candidates are sampled from a multi-variate normal distribution $\mathcal{N}(m, C^T)$ with the new mean m and the adapted covariance matrix C^T. In order to achieve a better convergence, a modification of the standard CMA-ES based on [4] was implemented, in which the non-diagonal elements of C^T are set to zero. This reduces the complexity of CMA-ES due to less calculation efforts when adapting the covariance matrix.

This evolution-process is performed iteratively until a convergence criterion is met (**Figure 1**).

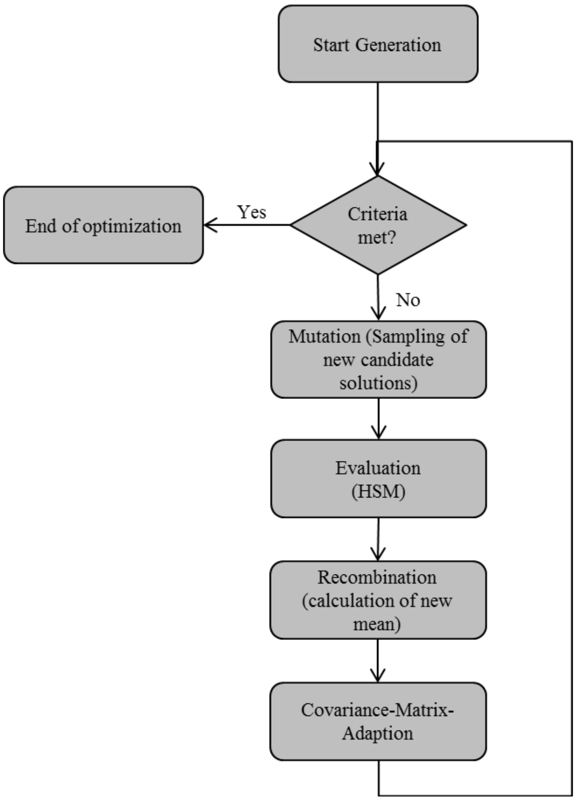

Figure 1 Scheme of the optimization process

An advantage of the CME-ES compared to a Genetic Algorithm is that the only parameter to be determined is the size of the population, since the variances of the optimization parameters is determined by the algorithm itself.
As a result of the power system optimization, the total energy cost can be calculated with the annuity value of the investments, maintenance and the operation costs of the system according to equations (2)

$$C_{electricity} = \frac{a_{invest} + C_{Maitenance} + C_{operation}}{E_{consumption}} \quad (2)$$

2.3 Power System Operation: Hierarchical System Management (HSM)

The operation of power system candidates created by the CMA-ES is simulated with a Hierarchical System Management (HSM), which is a time-step simulation according to a previously defined hierarchical strategy. The use of a HSM is motivated to achieve small calculation times for estimating the operating costs of the power system as well as enabling non-linear modeling of power system utilities such as storages. The hierarchical strategy is applied consecutively for each time step with respect to the results of the preceding time steps. A schematic overview of the HSM is shown in **Figure 2**.
The first step for determining the power system operation consists of balancing the load in each region with the non-dispatchable RES. Energy unbalances in each region will then be tried to be compensated via the grid. Calculation of the resulting power flow due to the compensation is done using a network-simplex-method. To keep the transmission losses as small as possible, transmission costs based on the ratio $line\ length/installed\ capacity$ are used within the network-simplex-method.

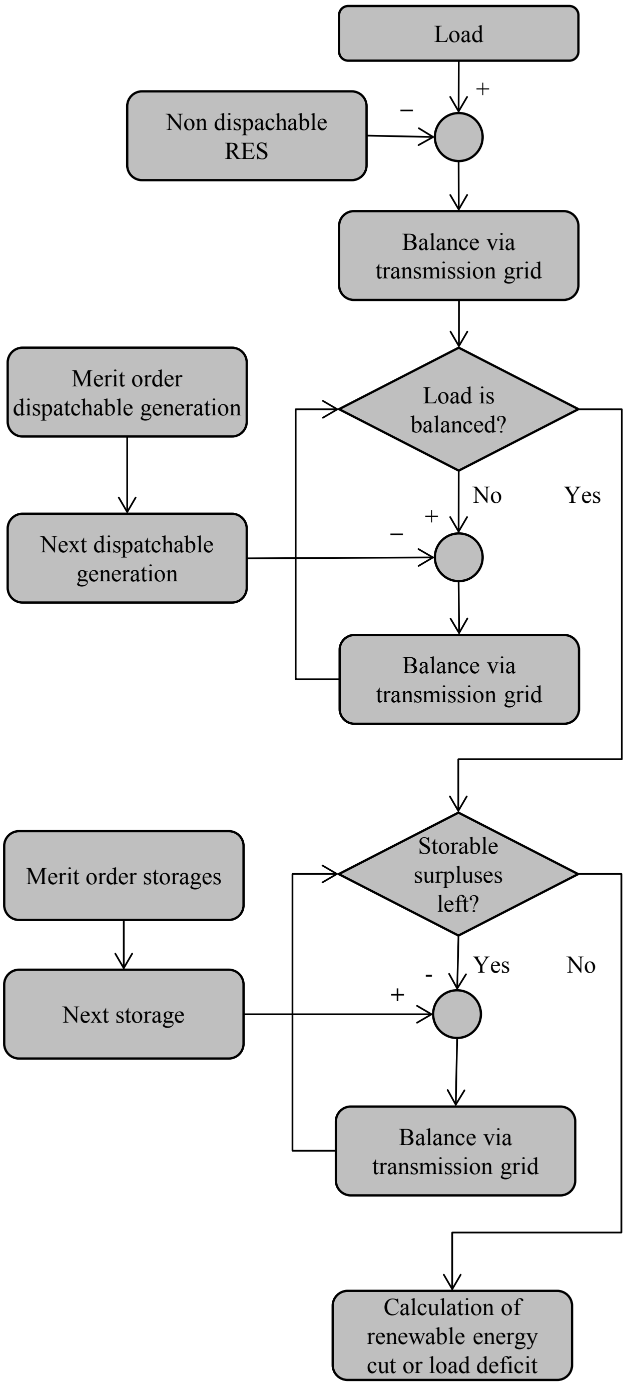

Figure 2 Operation hierarchy scheme used for estimating the power system operation

The next step consists of balancing the remaining load with dispatchable generation. Since the network-simplex-method is not able to differentiate between different generations technologies, the balancing is done iteratively for each generation type, according to a merit order list (priority). The methodology to assign a priority to the generation is shown in **Figure 3**.

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The first generation technologies in the merit order list are the ones with no operating costs, such as water turbines. Among them, they are ordered according to their efficiency, starting from the ones with the highest efficiency. The second priority consists of storage dischargers where their associated storage units have a future state of charge (SOC) bigger than zero. This future SOC is estimated for all storages within a specified timeframe in advance (for example 24 hours), considering only the load and the RES generation, and neglecting the maximum storage capacity and the grid. Storage units with a positive estimated future SOC are ordered according to their total discharging efficiency (storage and storage discharger), starting with the one with the highest efficiency.

Genesys is also been meant to take into account conventional power plants, such as gas-fired power plants, in order to consider the flexibility of these generators which can help to reduce storage need during the transition of the power system towards higher shares of RES. The third priority, which will be considered in a future version of Genesys, will have the conventional power plants ordered according to their operating costs. CO_2 emissions are considered throughout a CO_2 emission price, which is given as an input data.

The fourth and last step consists of charging the storages that have positive storage capability with the surplus energy from RES. The charging process is also done iteratively according to a merit order list, according to the total charging efficiency (storage and storage chargers). Same as in the previous steps, the grid is also used to balance storages in different regions.

As a result of this process, the operating costs of the system and the hourly energy deficit or surplus in each region is obtained. Deficits or surpluses are penalized by a user defined penalty costs for energy not supplied and renewable energy cut, respectively.

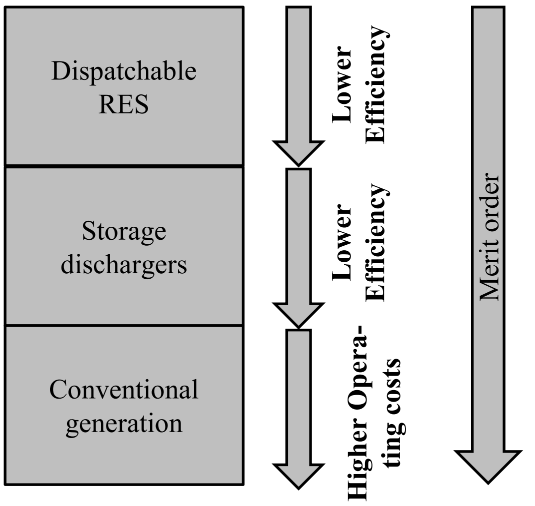


Figure 3 Merit order of dispatchable generating units for balancing the load

2.4 Optimal Power System Operation using CPLEX

As stated before, Genesys also enables to simulate the power system operation by means of a linear problem formulation, which is solved with CPLEX. The objective function of the formulation problem is to minimize the total operating cost of system. For a given power system (e.g. installed capacities of all network elements), the optimization variables are the hourly power generation of each generation technology, the power transfer between regions and the storage volume in each time step. In order to ensure a solution, a virtual generation and a virtual load with infinite capacity but high penalty costs are added in each region. The use of the virtual generation and the virtual load represents the expected energy not supplied and the renewable energy cut, respectively.

Constraints of the mathematical formulation are the supply of the demand in each region and for each time step, constraining the maximal generation to the installed capacity of the generation units, and the balance of the storage system. For the balance of the demand, a lossless transmission system is assumed.

2.5 Optimal Power System using CPLEX

The problem formulation of the optimal power system using CPLEX is an extension of the problem formulation of the power system operation presented in chapter 2.4. In this case, the installed capacities of the network elements, $P_{gen\,,max}$ for the generation and $P_{line\,,max}$ for the grid, and the capacities of the storage system $E_{st,max}$ are no longer given but also optimization variables. The objective function is therefore extended to incorporate the annuity value of the installation costs and the maintenance rate of the power system utilities. The new added constraints in the LP formulation are shown in equations (2) – (5).

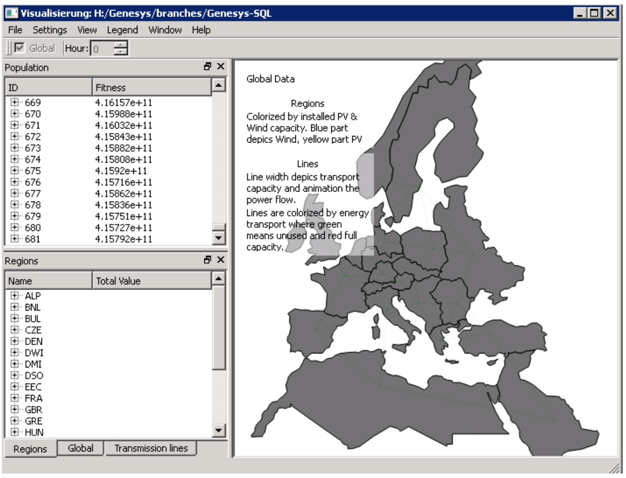
$$P_{gen}(t) - P_{gen\,,max} < 0\ \forall t \tag{2}$$
$$E_{st}(t) - E_{st,max} < 0\ \forall t \tag{3}$$
$$P_{line}(t) - P_{line\,,max} < 0\ \forall t \tag{4}$$
$$-P_{line}(t) - P_{line\,,max} < 0\ \forall t \tag{5}$$

2.6 Visualization tool

In order to have a graphical view of the optimal power system, as well as its operation, a visualization tool is also implemented in Genesys.

The visualization tool is written in C++ and uses the cross-platform application framework Qt. The main window of the visualization tool is shown in **Figure 4**.

The visualization tool also incorporates different export features. The charts displayed can be exported in PNG, SVG or EMF format. Also, a video of the the power system operation can be exported in AVI, MPG or GIF format. Finally, the installed capacities as well as the power system operation can be displayed as a table, and exported in a CSV format.



ID	Fitness
669	4.16157e+11
670	4.15988e+11
671	4.16032e+11
672	4.15843e+11
673	4.15882e+11
674	4.15808e+11
675	4.1592e+11
676	4.15716e+11
677	4.15862e+11
678	4.15836e+11
679	4.15751e+11
680	4.15727e+11
681	4.15792e+11

Name	Total Value
ALP	
BNL	
BUL	
CZE	
DEN	
DWI	
DMI	
DSO	
EEC	
FRA	
GBR	
GRE	
HUN	

Global Data

Regions

Colorized by installed PV & Wind capacity. Blue part depics Wind, yellow part PV

Lines

Line width depics transport capacity and animation the power flow.

Lines are colorized by energy transport where green means unused and red full capacity.

Figure 4 Main windows of the visualization tool

3 Exemplary results

3.1 Investigated situation

An optimization of the EUMENA Region, separated into 21 regions, was conducted for the year 2050 (**Figure 5**).

Figure 5 Map of the investigated regions

A total annual consumption of 8134 TWh for the EUMENA region in 2050 based on [5] was assumed and fitted into the regions. For this investigation, only Wind and PV Generation was considered (no conventional power plants). Technical and economic data assumed for wind turbines and PV is shown in **Table 2**

	Wind	PV
Installation costs (€/kW)	1000	600
Operation and maintenance rate (%)	2	2
Lifetime (years)	18	30

Table 2 Technical and economic data for Wind and PV

In order to balance generation fluctuations from RES, three types of storages systems were considered: hydrogen storage to represent long term storages, water reservoir representing middle term-storages, and NAS battery representing short-term storages. Water pumps and turbines of pumped hydro storage plants, as well as NAS battery chargers and dischargers were treated as a single unit, and therefore their charger and discharger capacities were set to be equal. This is due to the technical design of these systems (e.g. the power electronics of NAS batteries are used for charging and discharging). Technical and economical parameters adopted are shown in **Table 3**.

	Hydrogen	Pumped Hydro Storage	NAS Battery
η charger (%)	88	90	99
η discharger (%)	62		
η storage (%)	100	100	89
Installation costs chargers (€/kW)	300	550	100
Installation costs dischargers (€/kW)	700	550	100
Installation costs storage capacity (€/kWh)	0.3	20	111
Lifetime storage (years)	40	60	25

Table 3 Technical and economic data of storage systems (including charging and discharging units)

The total storage efficiency is the product of the charging efficiency, the storage efficiency and the discharging efficiency. In case of the NAS Battery, most losses occur in the battery due to electrochemical processes. In case of Hydrogen and Pumped Hydro Storages most losses occur during the energy conversion when charging and discharging due to mechanical effects.

All power system elements were assumed to have a discount rate of 6%/year.

3.2 Results

The results of the optimization using the combination of CMA-ES and HSM showed an optimal installed capacity of 2,694 GW for PV and 2,567 GW for Wind Turbines. This leads to an annual energy production of 5,850 TWh for wind and 3,530 TWh for PV, which means that around 60 % of the energy is produced by wind and 40 % by solar power. Also, a total transmission grid of 1,318,268 GWkm results from the optimization, which helps to compensate fluctuations in the generation and to transport RES generation from regions with higher potential. The spatial distributions of Wind and PV generators, as well as the transmission capacities between the regions are shown in **Figure 6**. From this figure it can be seen that most of the installed capacity of PV is located in the south, while most of the installed capacity for wind is located in the north, excepting in North Africa, due to the high wind potential of this region. The small share of PV generation in North Africa suggests reviewing the input data of solar radiation assumed for this region.

In addition to the generation and the transmission system, a total storage capacity of 756 TWh, with a total charging and power of 1,871 GW and a total discharging power of 1,148 GW are obtained. Detailed results for the different storage technologies are found in **Table 4**.

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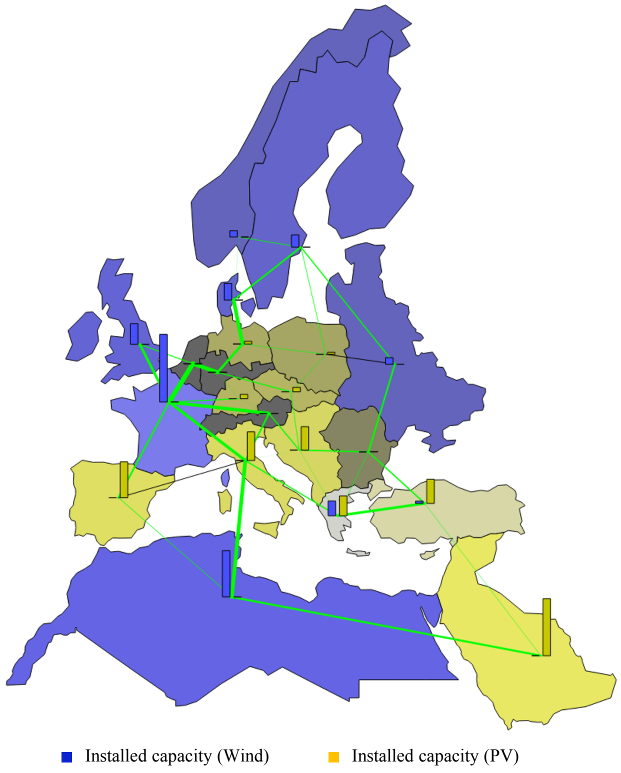

Figure 6 Optimal distribution of PV and Wind generators, and transmission capacities between regions

	Hydrogen	Pumped Hydro Storage	NAS Battery
Storage capacity (TWh)	751	5.3	0.67
Discharging power (GW)	440	394	312
Charging power (GW)	1,163	394	312

Table 4 Cumulated power and capacity of storage

The significant capacity of hydrogen storage obtained, which represents long term storage, shows the need of these types of storages to balance seasonal fluctuations in renewable power supply, avoiding to increase the necessary RES installed capacity to meet the load in periods of low RES generation (for example in winter), which would lead to high amounts of renewable energy cut in periods of high RES generation (for example in summer). For Pumped Hydro Storage and NAS Battery, a ratio energy to power of 13 h and 2 h, respectively, was obtained which suggest that these types of storages are mainly used for peak shaving and daily fluctuations.

The total electricity costs of the obtained power system are calculated to be 8.06 ct/kWh. The highest costs share is 3.56 ct/kWh due to the Wind, followed by 1.85 ct/kWh due to PV, as shown in **Figure 7**. Together, they cause around 67 % of the total energy costs. The remaining 33 % of the costs are explained by the storage (20 %) and the overlay-grid between the regions (13 %).

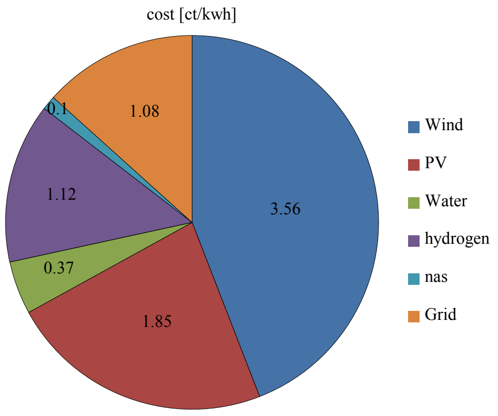

Figure 7 Cost structure of the found power system

4 Summary and future prospects

In this paper, the optimization tool Genesys was presented. Genesys optimizes the capacity and allocation of RES, the storage system and transmission network in order to get minimal overall economic costs. The optimization process combines a covariance matrix adaptation evolution strategy (CMA-ES), with a time-step simulation based on a Hierarchical System Management (HSM).

An exemplary optimization of the EUMENA region for the year 2050, considering 100 % RES generation showed a significant need of storage and transmission capacity, in order to compensate generation fluctuations from RES.

Further investigations with Genesys will consider conventional power plants, other types of storages and transmission system technologies, as well as political constraints such as minimum self-generation in each region.

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