Spatial and temporal power flows between regions with a power supply of 100% renewable energies in Germany

Technical University of Cologne, Masterseminar, under the leadership of
Ph. D. Eberhard Waffenschmidt
Köln, Deutschland
Daniel Korber (B.Eng.), Momoko Kristuf (B.Eng.)
korberd@gmail.com, momoko.kristuf@th-koeln.de

***Abstract*— With the spread of renewable energies in Germany there is a discussion whether the current structure of the electricity network is appropriate, or it must be adapted to the changing energy sector. For the analysis and evaluation of this question a simulation tool is designed with a user interface that allows the user to calculate and visualize power flows between regions. Based on the simulation a scenario has been developed, in which the expansion of renewable energies concerning regional potentials can be accomplished. It has been found that a widespread renewable energy production lowers the grid stress. By using energy storages peak loads can be shifted from very strong regions. Because of high regional differences of consumption and production potential it is not possible to build up self-sufficient working grids in all administrative regions in Germany. Therefore, an over regional electricity grid is indispensable.**

I. INTRODUCTION

The federal government has the default set to increase the share of renewable energies in electricity production to at least 80% by 2050 [1]. In the long run, a power supply with 100% renewable energy is required. In order to achieve a transformation of the electricity supply systems to renewable energy, fluctuations of energy through storage, networks and controllable production from renewable energy sources must be adapted to the electrical consumption. For this reason, there is a discussion in Germany about the ideal places and the ideal amount of renewable energy production and if this leads to new requirements on the existing power grid. There are voices that promote the expansion of the transmission network with high voltage power lines, while other voices prefer a cellular network structure and a decentralized approach with local stores. There is no basic data available to proof those statements. For this reason, several student projects at the Technical University of Cologne have collected and calculated temporally and spatially resolved supply and demand data in Germany from publicly available sources. There is only data from renewable energies. To evaluate the data a simulation tool with a user interface in the programming environment MatLab was designed. With this program power flows can be calculated and visualized between regions.

II. STATE OF THE ART

There are various examinations about the role of renewable energy production and its effect towards the power grid. In the following lines there are to approaches shortly explained. The first approach is a project developed at RWTH-Aachen with the name GENESYS. It deals with the optimization of the energy supply system with a focus on Europe, North Africa and the Middle East.

An iterative algorithm scales parameters to optimize the international power grid with the goal to minimize cost effects. Beside renewable power plants in the calculation are still fossil fuel power plants considered.

Parameters of the program are energy storages and national and transnational power lines.

It also takes the legal framework as well as the regional weather and consumption data into account [2].

The results of the project directly address the economic implementation of the European energy policy. It also considers conventional power plants. The approach presented in this paper has the focus on a complete conversion of the electric energy supply in Germany adapted perfectly to the grid.

An investigation, which deals with the full supply by renewable energies in Germany, is the VDE study "The cellular approach".

The goal of this study is it to give a statement about a cellular energy supply approach and its requirements for power transmission. The transfer functions are derived for an assumed expansion of decentralized renewables. The energy transfer is

calculated by a linear system, which minimizes the products of transmitted energy and length of all connecting corridors.
The overall goal is a low power transmission over short distances. As a result, there are power lines who transfer no energy between many connecting corridors. The study shows the most appropriate corridors for power transmission based on the overall transferred amount of energy [3].
In the project that is presented in this paper the German power grid is simulated using the node potential method. Compared to real power grids the calculation is based on a dynamic behavior of all components in the network. In addition, the power peaks due to the fluctuating power generation can be considered for the evaluation of ideal power lines, because the resolution of the data is 15 min. In comparison the data from the VDE studies only consider the annual energy.
In the following chapter it will be explained how the basic data was accomplished.

III. DATA FOUNDATION

The following section describes in brief points the records on which the simulation is based. There is data for all 40 government districts in Germany. In the following they are also called regions. Each data set has quarter hourly renewable generation and consumption data from 2011. It must be said that the paper "Transmission System Simulation: Presentation of delivery and load profiles with a Choropleth map" gives a more detailed description of the data rate determination [9].

a) Consumption data

The consumption data created for each region have been developed with the help of standard load profiles based on the number of inhabitants of each region. The profiles contain the areas business, industry, agriculture and households. The consumption of Germany that is not included in the standard load profiles were scaled based on the consumptions of the federal states.

b) Generation data

The electrical generation from renewable sources is mainly produced by the sectors wind, bio gas and solar energy.

1) Hydro power

The data set of the hydroelectric power stations was created mathematically. The energy produced can be determined by the installed capacity of the hydropower plants of each region and the rainfall in the region.

2) Bioenergy

The energy generated by the bioenergy power plants is simplified taken as base load. The installed capacity of each region determine the power generation over the time.

3) Wind power

The production over the year was determined by the installed capacity and the weather records of the regional wind speeds for each hour. After that the data set was interpolated to quarter hourly values.

4) Photovoltaics

The electrical energy generated in 2011 from photovoltaic power plants are based on a normalized to peak power data set of the company SMA Solar Technology AG relate [4].
The data set shows the solar course of a photovoltaic system depending on the location and the season. The data is divided on postcodes and available at 15-minute intervals.

For the simulation, the postcode areas have been allocated to the 40 regions. The solar production of each region was based on the photovoltaic performance of each federal state (by source [5]) projected to the regions.
The records are displayed graphically in figure 1. The production data are accumulated.

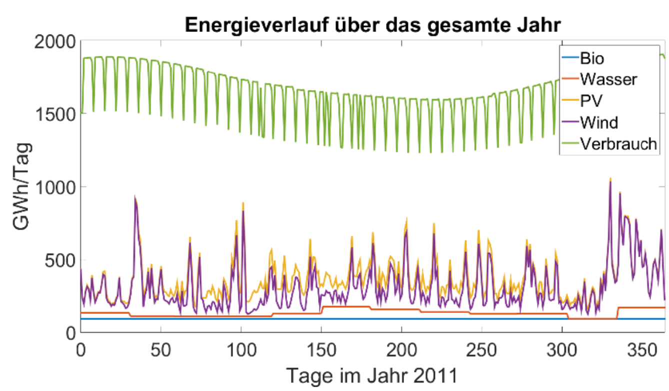

Figure 1: Production and consumption in Germany throughout the year

IV. DISTRIBUTION ALGORITHM

On the basis of the records, created for each region, the program can calculate a surplus of production or a production deficit for any date. The power grid is idealized assumed to be a linear network. Each region receives a connection (line) to its neighboring regions. In figure 2, the compounds are exemplified.

Figure 2: Created power grid

The power flows between regions are calculated using the nodal analysis. Power flow optimization by nodal analysis means minimizing the square of the power flows. This corresponds to the losses, as losses are approximately proportional to the square of the power flow. An idealized illustration is shown in Figure 3.

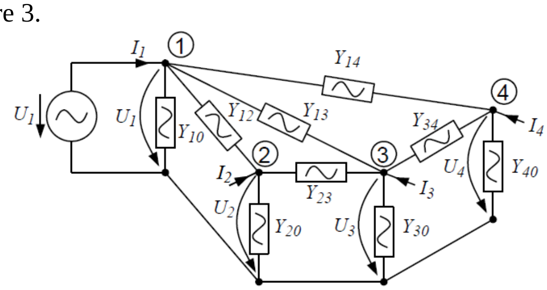

Figure 3: Exemplified illustration of the power grid [4]

For such a network, the power flows and the potentials of the regions can be calculated by the following formula:

$$\begin{pmatrix} I_1 \\ \vdots \\ I_n \end{pmatrix} = \begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{pmatrix} \begin{pmatrix} U_1 \\ \vdots \\ U_n \end{pmatrix} \qquad \{1\}$$

The generated power in each region, so in each node, corresponds to the currents (I_1 ... I_n in formula {1}), which flow into the network.
It applies:

- Nods ⇔ Regions
- Current (I) ⇔ Power
- Voltage (U) ⇔ Power potential

The admittances between regions represent the reciprocals of the line resistances. They shall be adopted idealized by one in the calculation. The admittances to the neutral conductor are the same for all regions and defined with 0.0001.
There are no differences in the line lengths and the line characteristics. The admittances take place in the conductance matrix (variables a_{11} *to* a_{nn} in formula {1}).
It consists of 40 regions from 40 rows and 40 columns. On the main diagonal are the sums of the conductance of all branches that are connected to the specific node.
On the other points is the negative sum of the conductance between the neighboring nodes (-1).
If there is no direct connection between two nodes, a zero is entered at this point [5].
The surpluses or deficits generated at any time in each region will be divided equally between the application of the node potential method.

V. IMPLEMENTATION OF ENERGY STORAGES

A grid shifts power spatially. Due to a strongly fluctuating production there are temporarily very high power peaks that must be dissipated via lines and decreased in other regions. Moreover, power lows can occur that have to be compensated. Both problems can be solved through energy storages.
It is questionable where and how many energy storages should be into the power grid in order to ensure cost-effective and stable operation.
There are two different algorithms for energy storages implemented in the tool. They will be described in the following lines.

a) The regional energy storage

When using the local energy storage, the installed capacity and power is selectable for each region via a mask.
The storages are located in the algorithm of power grid. This means that each region initially stores surplus or a deficit of energy from memory then refers only a potential in the distribution system receives. The charging and discharging efficiency of the storage is implemented with 90%.
In the algorithm the storages are located between the power production and the power grid. This means that each region stores surplus or gets power from the storage before the region receives a potential in the distribution system. The charging and discharging efficiency of the storage is 90%.

b) The virtual storage

The integrated virtual storage is an ideal storage. The power outputs are distributed as usual equally across all regions. For each time point occurs a positive or negative energy level in Germany. If there is a surplus, it is stored in the virtual memory. If there is a deficit and the energy can be covered up by the virtual energy storage. The virtual storage has no limitations in capacity, performance or efficiency. It is independent of the technology. The virtual storage can also be interpreted as an export amount. As long as it comes to surpluses, its energy content is growing.
From this, statements derived about which performance and capacity the overall storages of Germany should have to cover a 100% electrical renewable energy supply.
The virtual storage corresponds to a large quantity homogeneously in Germany distributed storages, all of which are connected to the power grid and communicate with one another.
The next chapter shows how the simulation tool is used and how the results should be evaluated.

This chapter introduces the application of the program in broad terms. A more detailed description is implemented in the tool information boxes. The user gets the opportunity to scale both the generation and consumption in all 40 regions. As described an energy storage can be integrated in addition. Processing the program, the user interface shown in Figure 3 opens.

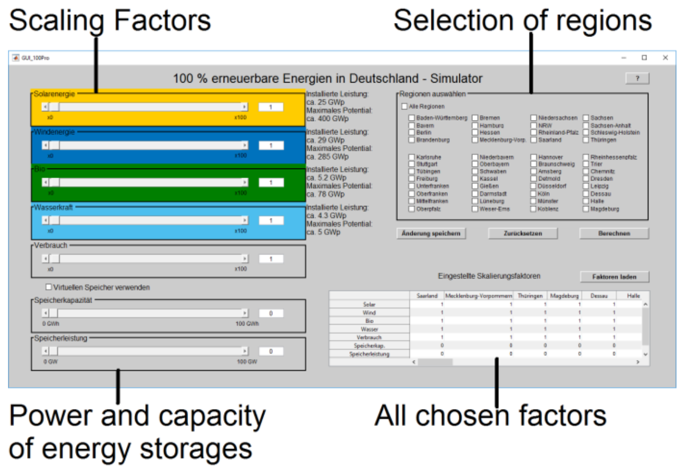

Figure 3: GUI - 100 % renewable energies in Germany - Simulator

On the right side there is a selection of all regions through checkboxes. The scale of production and consumption is determined by sliders or their associated text fields on the left. The factor of one means that the respective data goes directly and unchanged in the calculation. A factor of two corresponds to a doubling of values.

The capacity and performance of the energy storage will be determined by absolute values. If there are overlapping changes, the respective steps have to be confirmed via the button "Änderungen speichern”.

The table shown on the bottom right gives an overview of all defined factors. It is possible to save the created parameters in the end of the simulation. Those saved parameters can be loaded with the button “Faktoren laden”.
The calculation starts with the "Calculate" button.

After the data has been processed, the user interface shown in Figure 4 will appear. On the right side, the time interval of the year can be selected using the "Ausführen" button. The results are visualized on the map of Germany.

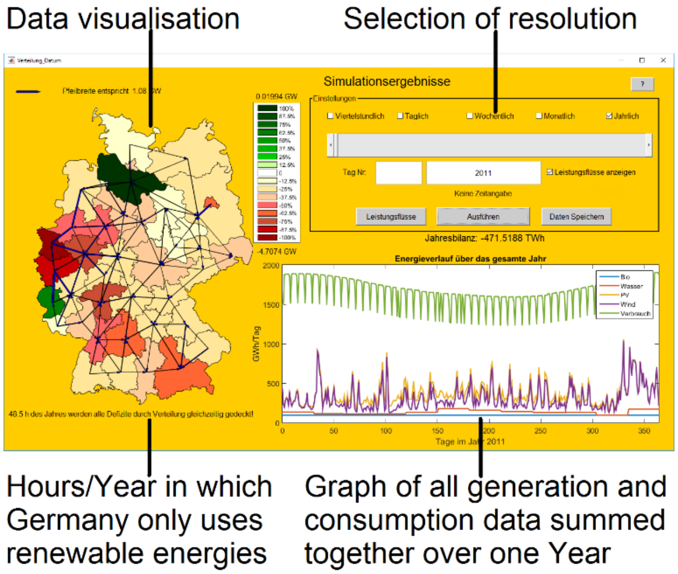

Figure 4: GUI – Simulation Results

The graph on the right side in figure four shows the generated renewable power and consumption of Germany throughout the year. For a better view see also Figure 1.

The map shown is divided into 40 regions. The difference between the production and consumption of the specific time step is color-coded. The color red corresponds to a deficit and the color green to a surplus of energy. The gradient is adjusted by percentage of the strongest region.

The width and direction of power flows is indicated by blue arrows. They show the capacity of the respective compound. To get better a program performance, the power flows can be hidden by using a checkbox.

The, for each time step, calculated power flows, generation and consumption data can be saved through the button "Daten speichern" in a selectable folder. The program generates files in *.txt* format those files can be analyzed with Excel.
In order to make a detailed analysis of power flows, a further user interface was designed. You can select "power flows" over the button to get to the interface in figure 5.

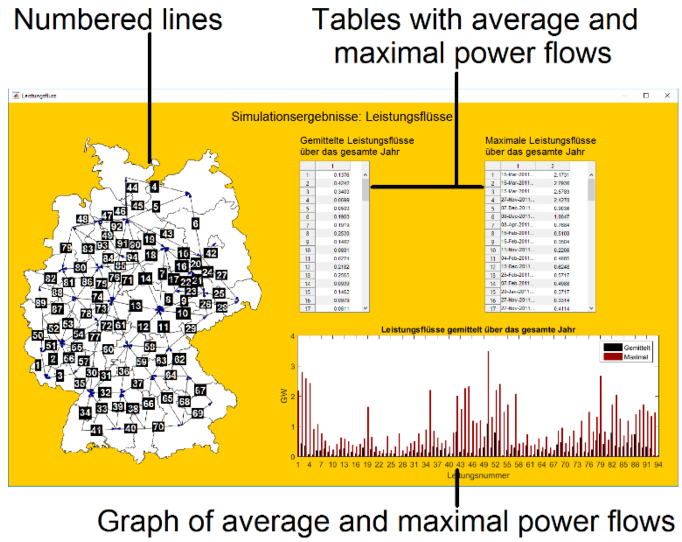

Figure 5: GUI – Simulation Results: Power Flows

The regions themselves are linked by 94 compounds. They are represented on the map of Germany. The mean values of power flows and the extreme values of the year are shown in the two tables on the top right. In addition, these values are displayed graphically on the bottom right.
With the compiled program can be examined, in which regions the expansion of renewable energies is particularly recommended. The Overarching objective is a stable power grid with short transmission paths for the electric power supply. As a part of the project there was a 100% renewable and grid friendly scenario developed. It is shown in the following chapter.

VI. 100 % Renewable Energies – Szenario

The expansion of renewable energy power plants depends on the regional circumstances. These include the supply of space and other especially the weather conditions. For example, the solar irradiation in Freiburg is higher than the radiation on the North Sea [6].
On the other hand, in northern Germany there are ideal surfaces for the use of wind energy both on and offshore. For the created scenario, the potential of all mentioned renewable energy producers was determined for each federal state [7]. The focus in this scenario is scaling up the solar and wind power production. To get a higher base load the bioenergy production in each region was increased by 50 %. The hydro power production remained the same.

The strong fluctuating renewable energy production can be counteracted by the combination of different types of

production. An optimal relationship between wind power and solar energy is a rate of about 70% wind energy and 30% of electrical energy from photovoltaic systems [7].
By considering the regional potentials and the ideal ratio of wind and photovoltaic, there were production factors for each federal state determined that enable Germany to produce its needs over the year itself.
Figure 6 shows exemplary the expanded production for the states of North Rhine-Westphalia (NRW), Bavaria and Baden-Württemberg (B-W).

	Vorher		Nachher		Potential	
	Solar	Wind	Solar	Wind	Solar	Wind
NRW	2.2	1.0	66.8	41.3	72.2	41.3
B-W	3.5	1.3	21.9	43.5	24.7	45.0
Bayern	7.8	1.3	27.1	76.4	31.0	80.0

Figure 6: Chosen wind and solar power scaling factors in the unity TWh/Year

The state with the highest electric consumption is Nordrhein-Westfalen. At the same time the potential for renewable energy due to the dense population is relatively small. The optimum ratio of wind and solar energy cannot be adjusted. On the other hand, Bayern has a very high wind potential that is mostly exploited in this scenario. The graphical analysis of the scaled generations is set out in Figure 7.

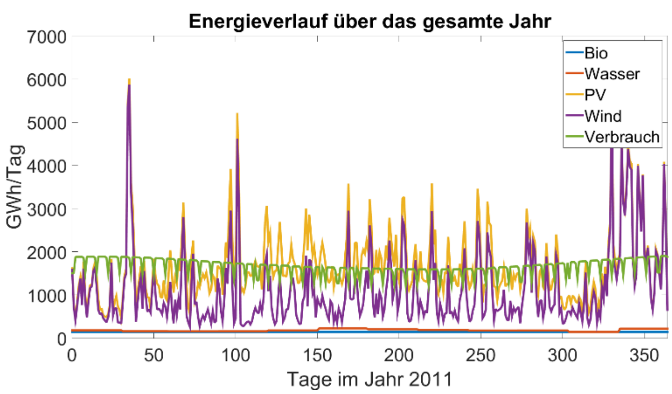

Figure 7: Graphcal energy history of Germany

The annual balance sheet (= total production - total consumption) of the scenario created is 7.2 TWh. It is clear that the wind generation leads to very high peak loads that have to be shifted through energy storages.

The simulation allows the use of individual regional storage for influencing the electrical power distribution.
Due to the regional storage algorithm there were storages implemented in the most productive regions. These includes the regions Freiburg, Münster and Gießen. Their energy storages have been implemented with a capacity of 20 GWh and a capacity of 75-100 GW.
For comparison, the simulation results of the set parameters are shown in figure 8 and 9. Figure 8 shows the simulation without implemented energy storage systems. On the other hand, shows figure 9 the same scenario with integrated energy storage systems.
In figure 8 it is clear that there is a production surplus in the wind powered north. More over the expanding of wind and solar power leads to a significant surplus in parts of the southwest of Germany. Without the use of energy storages, the results show that the production can directly cover 3520h the consumption of the year.

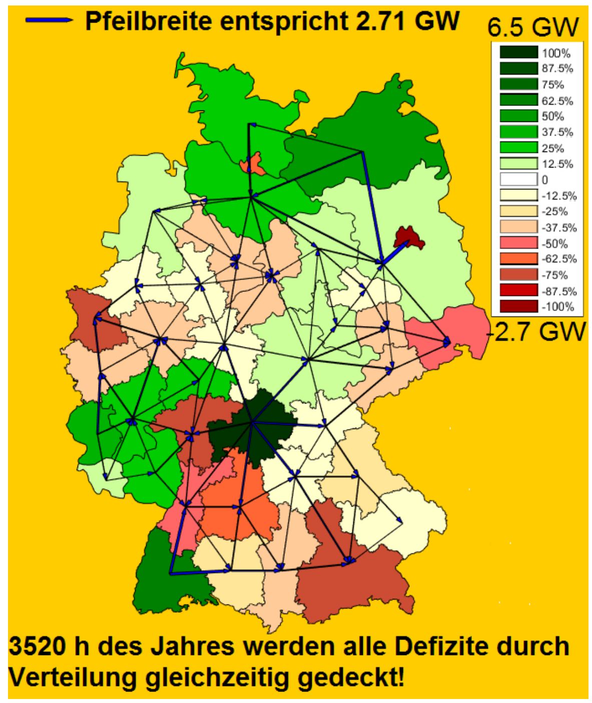

Figure 8: Visualized simulation results without the use of energy storage systems

Figure 9 shows that the average power flows have declined over the year by 0.3 GW. Simultaneously, the consumption is covered by only 2858 h of the year directly from renewable energy sources. The annual balance sheet is lowered to 3.5 TWh. This is due to efficiency losses and the fact that at the end of the simulated year there a few energy storages are partially charged.

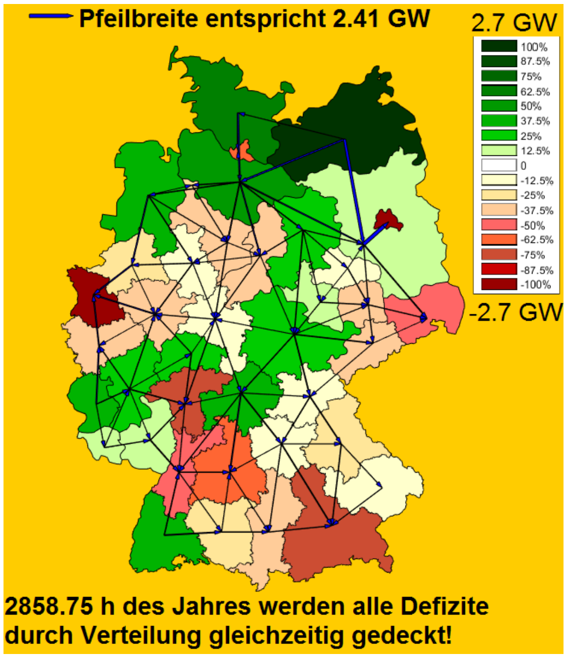

Figure 9: Visualized simulation results with the use of energy storage systems

It follows that a purely regional used storage in a cellular network leads to a reduction of the self-sufficiency level. However, especially the peaks of the power flows can be shifted. This is shown by comparing the figures 10 and 11. There, the maximum power load of the year (red) and the average power flow (black) is displayed for each compound.

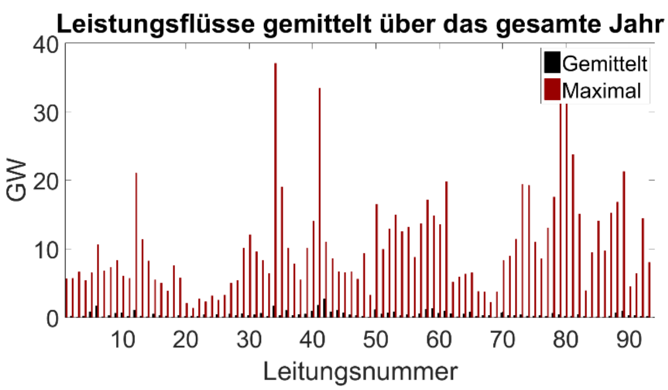

Figure 10: Maximum and average power flows without the use of energy storage systems

The idealized network consists of 94 lines. For example, the lines 34 and 41 of the Freiburg region (southwest) describe the compounds to the neighboring regions. The power peaks of lines 78-82 are around Münster.

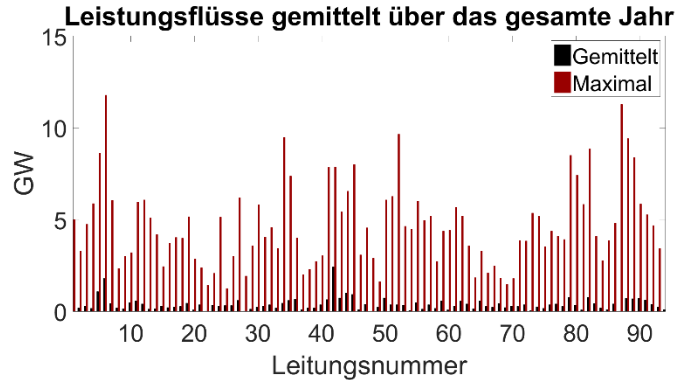

Figure 11: Maximum and average power flows with the use of energy storage systems

Through the use of storing the power peaks of almost 38 GW are reduced to 12 GW. The lines of the ideal network are visible relieved.

The implemented virtual storage takes place after the power distribution for correcting regional deficits and surpluses. As already explained, the virtual storage has no limitation in capacity and performance. The program specifies the maximum amount of energy stored and the maximum charge or discharge power. It behaves like a plurality of communicating energy storages, which are integrated into the grid of each region. In the established scenario, the maximum amount of energy stored is 48.4 TWh. The maximum capacity is 298 GW. This ideal working memory reaches 7805h a year, in which consumption is covered by renewable energies. This is due to the fact that the storage is completely discharged at the beginning of the year. If the operation of storage spread over the year, a complete coverage of the energy demand would be possible.

All in all, the scenario shows that there is enough potential to cover the whole energy consumption with renewable energies. The potential of many regions were not used to its full expansion.

A completely autonomous power supply is only possible if the balance sheet produces significantly more energy through renewable energy than the absolute demand. In addition, it is necessary to implement large and powerful storages depending on their location. A purely cellular powered network structure is only useful if the regions have enough potential for self-sufficiency. Otherwise, it is strongly recommended to integrate weak regions into the grid and to support them meaningful about the use of storage.

VII. DISCUSSION

This chapter deals with the significance of the overall results of the student projects.

A simulation tool has been created, that mathematically processes and visualizes the regionally disaggregated consumption and production data. The primary objective is it to give professionals a way to investigate the in the public discussed demands, such as the need to develop additional power lines to investigate.

The power generation through renewable energy is divided among many individual power plants. There is a lack on time and location-resolved production data.

For this reason, temporally and spatially resolved supply and demand data in Germany, from publicly available sources, were collected and processed. The records are for the reference year 2011. Due to the lack of real recorded performance data there has to be done compromises. For example, the solar data had to be calculated by using scales for each region. This and other already described measures for the production of records lead to a dataset that is near to the real production of 2011, but it is not displayed exactly the same. Nevertheless, the data are sufficiently accurate to provide a basis for discussion.

The idealized linear network does not match the real German power grid. There is no line characteristics and no direct connections skipping a neighboring region.

The focus is on the analysis of power flows. The consideration of the current network takes place purely national and deliberately avoids import and export of energy through the European network. The nodal analysis calculates the potentials of the regional production and consumption and determines a realistic picture of the energy transfer of the German electricity grid.

VIII. CONCLUSION

The created simulation program does not only produce relative visualizations of records. It can also create scenarios for the investigation of cellular networks by selecting individual administrative districts.

The program was designed with the possibility to change the data sets. In this way updates of the records in terms of the real completed steady expansion of renewable energies are possible and recommended.

To improve the quality of investigations it is further recommended to modify the storage algorithm and secondly to implement a flexible bioenergy production.

Ideal would be a storage algorithm in which the regional implementable storages operate in dependence of the total production and total consumption in Germany.

Bioenergy gets a special role through its ability for flexibility. The energy production is variable and can be operated so that it compensates lacks of production and shuts down through production peaks.

REFERENCES

[1] Bundesregierung – Energiewende – https://www.bundesregierung.de/Content/DE/StatischeSeiten/Breg/Energiekonzept/03-erneuerbare-energien.html (Accessed 14.06.2016)

[2] RWTH Aachen – Projekt: GENESYS – http://www.genesys.rwth-aachen.de/index.php?id=startseite (Accessed 27.09.2016)

[3] VDE – Studie: Der zellulare Ansatz – https://www.vde.com/de/smart-grid/Seiten/vde-studie-der-zellulare-ansatz.aspx – (Accessed 27.09.2016)

[4] SMA – Solare Verteilung BRD – Niestetal 2014

[5] Förderal Erneuerbar – Landesinfo - https://www.foederal-erneuerbar.de/landesinfo/bundesland/SH/kategorie/solar/auswahl/183-installierte_leistun/versatz/3/jahr/2009/ordnung/2009/#goto_183 (Accessed 28.07.2016)

[4] TH Köln – Script „Elektrische Netze“ by Prof. Dr. Eberhard Waffenschmidt (Accessed 28.09.2016)

[5] ET-Tutorials – Knotenpotentialverfahren – http://et-tutorials.de/5205/knotenpotentialverfahren/ (Accessed 28.09.2016)

[6] Renewable-Energy-Concepts – Sonnenkarte - http://www.renewable-energy-concepts.com/german/sonnenenergie/basiswissen-solarenergie/geografische-lage-kwhm2.html (Accessed 14.06.2016)

[7] Förderal Erneuerbar - Potential Windenergie - https://www.foederal-erneuerbar.de/landesinfo/bundesland/RLP/kategorie/wind/auswahl/305-potenzial_windenergi/#goto_305 (Accessed 23.09.2016)

[8] Waffenschmidt, Reinartz – „Paper: The optimal combination of energy storages, photovoltaic systems and wind turbines at local level” – TH Köln (Accessed 28.09.2016)

[9] Stefan Schaefer (B.Eng.), Aziz Ait Benomar (B.Eng.), Alexander Lenz (B.Eng.) – „Paper: Transmission System Simulation: Presentation of delivery and load profiles with a Choropleth map” – TH Köln (Accessed 28.09.2016)