Energy Modelling in Rural Areas with Spatial and Temporal Data in Germany and Czech Republic

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Abstract: One of the major challenges for the energy transition is to reconcile variable renewable energy production with stochastically changing energy demand including the pursued changes in e.g. transport like electro mobility. This requires smart systems that should be designed to minimize balancing and transmission costs. The design and modelling of such systems requires high resolution energy generation and demand data, which usually either do not exist or is not available. Methodologies to address this lack of data populate scientific literature but its replicability is limited by an inadequate level of detail in the description of the methodologies and to a larger extent by the absence or low quality of basic data. This manuscript summarizes several years of research in energy modelling using Geographical Information Systems as well as spatial and temporal data of the rural areas in Bavaria (Germany) and the Czech Republic. Data requirements for energy demand and energy supply including different types of users and technologies are addressed. Irreconcilable data gaps are presented, examples to fill data gaps as well as recommendations for future necessary developments are provided.

1 INTRODUCTION

When analysing energy demand and supply in large areas, especially the exact localization is of major importance. This is especially true when considering renewable energies. They are less predictable in their production outputs than fossils and thus may induce great instability for the grid. (see, e.g., Passey et al., 2011). Furthermore, user related changes, the promotion of electro mobility, the increased use of electricity as primary source of energy and migration from the land induce an increased electric energy need for a shrinking number of citizens when considering rural regions (Valdes et al., 2019). The question raised for every community and regional government facing depopulation issues is therefore, how to tackle these rising issues by simultaneously minimizing costs of investments. The more detailed one could assess the current demand and supply capabilities, the current load of the electric grid as well as surrounding factors, the better forecasts and alternative scenarios for a cost efficient and sustainable development can be implemented. The results of such models are indispensable for regional planners, utilities and policy makers in order to plan future energy supply in a cost efficient and consumer friendly way.

High spatial resolution data of grid loads and capacity measures as well as electric energy consumption by different sectors are important factors to be considered. Current trends need to be evaluated by estimating its future impacts. One such major trend of today, is the introduction of electro mobility which is pursued by almost every country, and as a consequence uncoordinated charging events of electric vehicles might have negative impacts on the resilience and economics of an electrical system (Mu et al., 2014). Uncontrolled charging load of electric vehicles can generate, among others, voltage drops that degrade the power quality of electricity distribution systems (Foley et al., 2013). Therefore, the placement, sizing and supply of infrastructures such as electric vehicles charging stations needs to be carefully assessed.

Throughout the past years, research questions related to above mentioned topics were addressed manifold and in an incremental way in international scientific literature relying on geographical information systems as well as spatiotemporal data and modelling (Pagany et al., 2018; Ramirez Camargo and

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Stoeglehner, 2018). The main obstacle remaining, is the acquisition of complete and high quality spatial and statistical data, especially when modelling energy infrastructures and related topics in rural regions. This study summarizes several years of working in geospatial energy system modelling. More precisely, this review will include conducted energy use plans and climate protection plans using a spatially explicit approach in Bavaria (Germany) and the involvement in ongoing projects analysing the developments of the energy system in the cross-border region between Germany (Bavaria) and Czech Republic.

The rest of this article is structured as follows: Section 2 presents the type of research questions that can be addressed. Section 3 describes the challenges of spatial explicit energy modelling in the cross-border region of Bavaria and Czech Republic and section 4 explains particular workarounds and the consequences of deriving electricity demand and supply data from other secondary sources. Finally, conclusions are presented in the last chapter.

2 ELECTRIC SYSTEM AND VEHICLE CHARGING INFRA-STRUCTURE MODELLING

The UN Environment Assembly promotes global standards for the use of renewable energies and the increase in energy efficient usage. Moreover, at the lower administrative levels, the transition to renewable energy generation and to sustainable electric transportation have become a priority (Cajot et al., 2017). To develop and propose new models, policies or energy saving measures, first of all the current state of the art in energy usage and production needs to be observed on a larger, detailed scale. For that, research questions according to current data availability standards are of major importance.

Urbanization, increased automation of production processes and electrification of the energy matrix does not only lead to higher energy requirements but additionally puts pressure on the electric grid. This is further intensified with an increasing share of distributed renewable electricity generation. Demographic changes and rural depopulation decreases energy consumption in rural areas and lead to sub-utilization of existing energy distribution infrastructures. Moreover, technologies are advancing in their energy efficiency and smart housing devices help to eliminate unwanted energy consumption. This simultaneous, interdependent and fast but partially contrary development has to be analysed and studied exhaustively because the decisions taken to maintain a fully functioning energy infrastructure, will persist for several decades.

Contemporary computational capacities and models offer unprecedented capabilities to examine future decision options about complex systems under a wide range of assumptions. Current important research topics include the integration of high shares of renewable energy generation technologies, which range from well-established ones, such as photovoltaics and wind power, to technologies that should solve the dispatch limitations, such as power to gas and renewable fuels. Furthermore, decisions must be taken about the mix of technologies to be adopted, storage and backup systems as well as the integration of new technologies that improve energy efficiency, such as heat pumps. Technologies that are significant hopes in the reduction of CO2 emissions of society like electric vehicles and carbon storages, are further topics that require thorough research and decision making. Most of these technologies, as well as their impact on the electric grid at the DSO and TSO levels, require not only model approaches that can deal with future uncertainties that grow with time (DeCarolis et al., 2017) but also high quality data that provide a solid basis. Otherwise, results and conclusions derived will be misleading.

Especially in the present discussion of expanding electro mobility, it is of high importance to know where exactly energy is produced and consumed. It is often mentioned that the stability and capacity of the electric grid in its current state would not suffice for larger penetration rates. Considering the suggestion for better, more detailed data, would help in identifying grid gaps. The identification of these gaps can provide opportunities for electric vehicle charging stations to stabilize the grid, similar to already existing models like the "Building-to-Vehicle" approach (Genikomsakis et al., 2016). Moreover, one of the most interesting questions for a researcher in the area of electro mobility is: what the role of the availability of charging stations on the transition to an e-mobility concept would be.

Modelling the electricity grid presents a huge challenge for any researcher working in the area of electro mobility and electricity system planning in general. The main challenge is associated with the level of resolution needed. In the case of future electric vehicle charging processes, particularly with regards to higher distance ranges of the vehicles, customers will want to be able to charge their cars faster. Hereby fast charging or hyper charging stations are needed.

E-mobility planning needs to forecast the future scenarios with high degrees of electric vehicles penetration rates. Thus the demand may require to increase the grid supply capacity to several times ≥ 150 kW at central intersection points. Building numerous charging points with capacities of 50 kW or higher on main traffic arteries may have a huge impact on the distribution and even the transmission grids (Nationale Plattform Elektromobilität, 2015).

It is apparent that many topics concerning electricity and infrastructure planning are of importance not only to private companies but to governments and the general public. A thorough knowledge of the topic is therefore indispensable to make valuable decisions for future electricity and mobility reasons. For this, high quality, spatially and temporally resolved data is necessary. Such data however is either non-existent, or very expensive and not affordable to research institutions, which leads to establishing second best results with workarounds.

3 WHAT IS MISSING AND AN IDEAL DATA WORLD

Every energy system modeller faces a double trade-off when designing an energy model. They have to consider both, the level of detail, as well as the scope of the model. Due to the absence of data, a higher number of hypotheses and generalizations are in place most of the times and huge deviations from reality may exist. Concerning the electric system the availability and reliability of data deteriorates with decreasing level of spatial and administrative aggregation. For instance, at the national level in Germany it is possible to obtain hourly data of electricity generation from fossil and renewable sources as well as demand data (see, e.g., Fraunhofer, 2019). The same applies to the electricity transmission system. Spatial and attribute data of the high and highest voltage electricity grids as well as the location and characteristics of the main fossil based energy power plants are easily available. In the German case, a list of all electricity generation installations larger than 10 MW including location and basic attribute data is provided by the State Grid Agency (Deutsche Bundesnetzagentur, 2018). However, at the state level there is no public data available beyond yearly accumulated electricity generation and demand of different economic sectors. At the district and municipality level, this kind of data is only available on request by local distribution system operators (DSOs). Going further to a neighbourhood or building level, such data might be available only if some sort of specific data gathering project has been conducted on-site. While data of renewable energy generation installations covered by the renewable energy law was systematized and made available to the public until 2014, there is no reliable source about these installations (when these are smaller than 10 MW) since then (Deutsche Gesellschaft für Sonnenenergie e.V. (DGS), 2016) and even less is known about shares and periods of self-consumption of the electricity generated by these installations when they are part of buildings. Similarly, data of the medium and especially low voltage grids are rare goods that are difficult to acquire even on request.

Ideally, electricity demand and generation data in a high temporal resolution would be available at the building level, while occupancy characteristics and economic use of each building are also known. This would include single family houses to industrial production buildings in all federal states of a country. The current data availability status is not only very far away from this ideal, but the ideal itself would race irresolvable data privacy and security issues. Therefore, a compromise to keep private data safe is necessary, when gathering data in high spatial and temporal resolution. Specialized scientific literature on data processing already offers attempts to develop methodologies of data aggregation that gathers the most valuable information for energy modellers by simultaneously avoiding privacy issues. However, even in the best of these cases very strong assumptions have to be made. For instance, the best guess about the electricity consumption profiles of industries in Europe can only be made by comparing them to data from the US (Voulis et al., 2018).

For Bavaria and the Czech Republic, key energy demand figures divided by type of economic use and generator are publicly available only at the state level (NUTS 1). Moreover, temporally disaggregated data about electricity consumption and generation is only available at country level (NUTS 0) by Eurostat.

Additionally, in the Czech Republic, at least standard load profiles of demand for different types of users are provided for NUTS 1. The Czech Energy Regulation Office (ERU) provides information about the location of every energy plant of the country, including for example photovoltaic panels installed by private households. The data includes the owner and installed capacity by type of primary energy but it does not include any information about its use and in some cases the street or cadastre reference is missing or incomplete. As of December 2018 around a third of a total of 1,746 generation installations selected in the south-east of Czech Republic did not contain specific information on its location or it was too vague to obtain specific coordinates; the same problem appears in Bavaria.

Accessibility to geodata of the existing power grid in Germany is heterogeneous and depends on the region and voltage level. To produce realistic input data for simulation studies, necessary data is not publicly available or cannot be obtained with reasonable effort in the context of scientific analyses. For example, the datasets provided by the Bundesamt für Kartographie und Geodäsie(AdV, 2019), provides the spatial situation of overhead power lines but they cannot be differentiated into voltage levels. Furthermore, the lower and medium voltage levels are missing completely.

Considering electro mobility planning, geo-referenced data that would indicate where car drivers stop mostly, occupancy rates of municipal parking areas and frequency rates of streets that are not typically large commuter routes are also missing. One ideal data option is a widespread data pool that indicates where people stop, for how long they stop and how frequented those locations are but if such datasets exist, it is mostly individually formatted and thus not applicable for larger research areas.

Another data issue is the large difference in the existence of information between urban and rural regions (Pagany et al., 2018). The less frequented an area is, the lower is the anticipated need for collecting it. Utmost of rural regions are characterized by countryside, national parks and rather small towns and cities. This type of geographic regions is well at the end of the “data food chain”. Not a lot of people live there and the need for transportation system- and energy grid system developments is lower compared to urban regions

Besides these local factors, the ability of the grid is important for this topic as well as roads and locations that raise a refuelling demand. In Germany, data on roads and its infrastructure is collected by the federal offices. This data nevertheless is very expensive, which is why many researchers replace it with OpenStreetMap road data. All other datasets required are not available in an openly collected way.

Combining this information with a comprehensive dataset of grid capacities and occupancies, would indicate the best places for recharging batteries without inhibiting customers in their daily routines.

For many workarounds, Volunteered Geographic Information (VGI) provides researchers with alternative data sources. In view of OpenStreetMap (OSM) data, some characteristics are apparent, that any researcher would consider as ideal: it is free, actualized constantly, detailed, rich and it is classified. Nevertheless, OSM data belongs to the group of VGI and thus contains common problems like its incompleteness, the reduction to geographic information only, and the absence of quality controls and therefore infrequent wrong information (e.g. outdated, closed sites). In an ideal world, the data provided by OSM would contain even more information than the geographic localization and rough classification.

Newly, OSM also tries to cover grid related information for energy modellers in the transmission and distribution sectors. OSM data with the tag “power” has been collected since the beginning of 2007 and includes not only high voltage transmission lines but also information on medium voltage transmission lines, transformers and other infrastructure. New projects are exploring the possibility to generate accurate distribution network data based on this initiative (for an overview see e.g., https://wiki.openmod-initiative.org;Rivera et al., 2017). OSM data thus provides a base of information that is not available in this form anywhere else.

4 WORKAROUNDS AND THE INEVITABLE

When considering such questions as addressed in chapter 2, many of the required data sets are either too expensive or just not existent in a format as needed. The high accuracy and level of detail that is necessary is difficult to access. Inevitable is that most of the data is in hands of administrative complex institutions or private sector organisations, that invest money to gather data, which leads to the need of selling it at a certain price, in many cases not affordable to research institutions. Moreover, in the worst cases, data are in private hands so that there is no way to access it or data is not being gathered at all due to above mentioned reasons.

4.1 Electricity Demand and Supply Modelling

For municipalities in Germany, methodologies to determine energy generation and demand in a spatially explicit way using GIS related to the topics named in section 2 can be found e.g. in (Bayerisches Staatsministerium für Umwelt und Gesundheit et al., 2011). Additionally, a review of methodologies for the determination of spatiotemporal data for Germany and Austria can be found in (Ramirez Camargo and Stoeglehner, 2018). In the case of Bavaria and the Czech Republic there are, however, thousands of municipalities. The required computational and monetary resources to model electricity demand and generation in the level of detail applied to municipalities would be immense. For instance, typical data used to locate demand in space and to calculate spatially potentials of renewable energy sources at the municipal scale are data of individual buildings in a 3D vector format with level of detail 1 (LOD1) or 2 (LOD2) from the Bavarian survey Agency (Bayerische Vermessungsverwaltung). These data exist in Bavaria but it is available only under request and monetary charge per object. The cost for all existent (several million) objects is prohibitive. The alternative that is free of charge (for educational institutions conducting research projects), are 2D vector data without attributes apart from the location and the address. In Czech Republic, the geodata infrastructure is expected to be modernized until 2020 and 3D vector data of buildings should then be available for the whole country (Janečka and Souček, 2017). For the moment, 2D data with multiple attributes is available to the public trough e.g. the INSPIRE program. In order to enrich these 2D Building datasets with attributes, such as size, use and number of households (in the case of residential buildings), further data, like high resolution digital surface models (usually also not free of charge), land use data and high spatial resolution population data might be used. However, new issues emerge due to the format, the spatial resolution and the creation and reference dates of the data sets. Taking this and the known limitations about the availability of time series of electricity demand (section 3) into account, the best spatial resolution that could be pursued for the generation of spatiotemporal datasets of electricity demand in Bavaria are municipalities and in the Czech Republic federal states.

In order to produce data sets displaying the electricity demand for each municipality as specific and near to reality as possible, workarounds were established. In Bavaria, due to a study on the share of renewable energies in place (Energie-Atlas Bayern ,2018), the consumption of electricity per municipality was calculated using the electric energy demand of manufacturing industries on district level, dividing it by the number of people working in those industries on the same level and then multiplying it with the number of inhabitants per municipality, working in the selected field. Additionally, the same was done with households and population sizes as well as employed people in other industries as the above. This calculation does not include electric energy needed by transportation systems.

While current demands of electricity are relatively easy to derive with calculations as the above mentioned, they are also only approximations how reality might seem, commuters are for example left aside. Forecasting the development of electricity demand however is even more difficult. Several aspects need to be taken into account, like future technological advancements, new ways of living (smart homes, heat through electricity, electro mobility, etc.) as well as demographic changes or rural depopulation and urbanization.

To develop a calculation for the future demands of electricity per municipality, the current electricity demand was distributed into the three sectors industry, agriculture and households. From there, LUISA data is used to match the current numbers with future estimations of land use and demographic developments. The LUISA Territorial Platform supplies data for the future estimation of land use and further indicators per km2, provided by the European Council (Barbosa et al., 2015). By combining the current electricity demands per municipality, differentiated into the three different sectors with the percent changes of rising or shrinking numbers of selected Land Use and demographic data, future electricity demands per municipality can be estimated. By introducing further factors, like technological trends, electro mobility or policy recommendations' induced developments, the estimations can be adapted.

In the case of existing renewable energy installations, apart from the data that has not been gathered at all (mainly installations smaller than 10MW since 2015), the major issue is the estimation of the output in a high temporal resolution. Usually, for municipalities, data from several installations can be generalized to all installations in the study area. Alternatively, data from a close weather station together with physical models of PV and wind turbines are used to estimate the output of installed capacities. In order to develop such an estimation for Bavaria and the Czech Republic without having to deal with incomplete data sets from hundreds of sources, we opt to use high resolution reanalysis data. The COSMO-REA6 regional reanalysis (Hans-Ertel-Zentrum für Wetterforschung, 2018) offer, among many others, the U and V components of wind speed at different altitudes, downward diffuse and direct shortwave radiation flux at surface as well as temperature data for the period 1995-2015 in hourly temporal resolution and 6 km x 6 km spatial resolution. These are not only complete data sets (full spatial coverage and time series without missing values) but they also have been validated and are in many cases more accurate than satellite imagery derived data (Ramirez Camargo et al., 2018). These data together with the models of PV and wind power serve to estimate the output of existing installations. However, it is impossible to correct cases in which the location or size of the installations are not available at all. To provide an accurate estimation of the output when the installations are integrated in buildings and the self-consumption rates are unknown would be further points to improve.

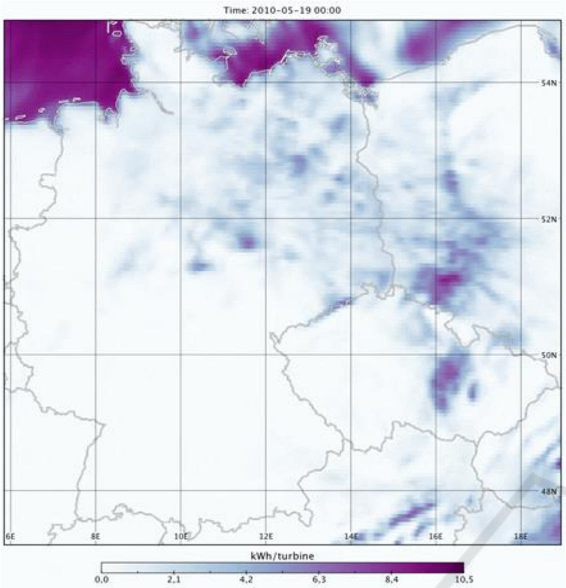

Figure 1: Example of one-time step (2010-05-19 at 00:00) wind power generation of a small wind turbine with 10.5 kW calculated using COSMO-REA6 reanalysis data for Germany and the Czech Republic [kWh].

In order to produce data sets of spatiotemporal potentials of renewable energy generation, a similar approach to the case of existing installations can be followed. COSMO-REA6 data can be used to easily generate long and high resolution time series of potential electricity generation for entire countries as presented in Figure 1. Therefore, the only requirement to create spatiotemporal datasets of potentials, is the identification of areas fulfilling suitability criteria for the deployment of certain technologies (e.g. small, medium and large wind turbines or free standing PV). These areas are defined using 2D building data, road and river data from OSM, official and free data of Nature 2000 areas, as well as water bodies and forest data from official sources and free data of land use. Apart from incomplete or inaccurate data, errors that are difficult to find and correct in this case are related to the reference date of the spatial data and changes that might have occurred until the day of calculation of the potential. For instance, buildings that do no longer exist may increase the supposed suitable areas or new buildings or infrastructure may transform suitable areas in now unsuitable ones.

4.2 Electro Mobility Charging Station Placement

Most research studies that focus on the modelling of charging infrastructure propose charging station locations dependent on different factors but all in urban, very densely populated areas. The methods with a greater resolution or accuracy are based on the collection of GPS data, as e.g. (Dong et al., 2014). Such methods imply the collection of data in a long time span and for different driver profiles, which requires a large quantity of resources the larger the area observed and the lower the density of traffic.

In order to make assumptions about user behaviour and charging events, Triebke et al., (2016) collected a large dataset. More than 15.000 charging events were accumulated and analysed in both rural and urban areas. In urban areas, charging behaviour is rather predictable and assessable, however in rural areas not. The occupancy rates are very low and random compared to urban areas. As highlighted before, in Bavaria and Czech Republic, there are hundreds of municipalities and the resources to model Electric Vehicle Charging infrastructures based on GPS data would have to be immense. With the purpose to provide these municipalities with a tool to design and develop new transport infrastructures Zink et al., (2017) and Valdes et al., (2019) established a model to define demand for electro mobility charging stations by help of designating a certain demand for energy to each Point of Interest in the project area based on OSM data. The project area is the border region between Bavaria and Czech Republic, which is a very rural region including a large national park. The presented workaround is based on Zink et al.,(2017), and extended by energy generation measures.

The charging demand calculation is based on a spatial statistical methodology considering demographic parameters, the distance of charging stations to chosen Points of Interest (POI's) (extracted from OSM) and time spent at the POI's according to different age groups.

In order to include OSM data in the model, it has to be first validated. Based on Valdes et al., (2019), the data is first "pre-validated", to concentrate on the relevant data sets and then processed in order to identify the relevant POIs. The validation process is customized to the South Bohemian and Bavarian regions as well as the model design defined in Zink et al., (2017). By processing data in the in Valdes et al., (2019) presented way, the electric vehicle charging model is filled with improved data, which allows to reduce a bias associated to particularities of OSM data.

The demand model furthermore contains the average time use per day, dwelling time at one POI, the penetration rate of electric vehicles and selected POI's. It allows to allocate an electricity demand to each POI and aggregate it at the municipal level (see figure 2). The models input data partly consist of national surveys without geographical differentiation which may be a potential source for biases as long as behaviour in rural and urban areas is significantly different, for example due to the availability and distance to amenities. Moreover, there is no common method of data collection and the classification of activities and time resolution is not the same in the German and Czech surveys.

The walking distance determines the optimal charging station placement within a region with high energy demand by minimizing the average distance to the surrounding POIs.

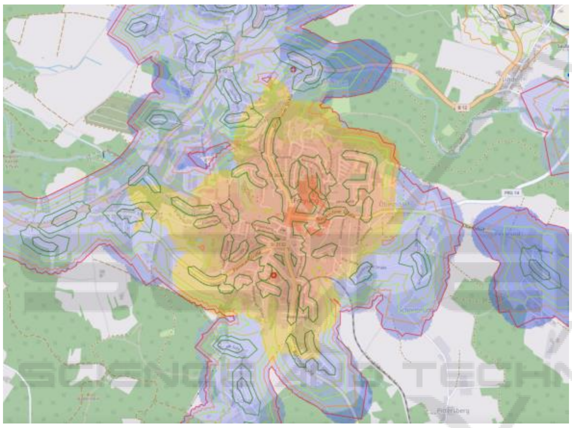

Figure 2: Example of Electric Vehicle Charging Demand and Walking Distances from POIs in Freyung, Germany.

The available electricity generation sites in the project region are estimated in their average energy supply capabilities is assessed and geographically localized using the methodology and data described in the section above. The geographical range to supply a charging station directly with the sites provided energy is enclosed. After both sides, the energy supply and -demand, are calculated and geographically displayed, areas with high demand and possible renewable energy supply indicate the best spots for charging stations.

With this model, possible charging station locations are not only bound to Points of Interest but also existing and potential generation sites that provide the charging stations with enough endogenous renewable energy to relax a possibly congested grid, not only in urban but also rural areas.

5 CONCLUSIONS

The more detailed and correct data is provided, independent of its content, the better and precise models can be used to estimate certain phenomena. Here, the focus was put on electricity contexts considering demand and supply potentials as well as electro mobility charging station placements. The future is known to be unsure, however for that, models are developed to establish a better forecast and to help policy makers and regional developers explore possibilities and make plans in order to supply the society with the right choices and capabilities. In order for these models to be as precise and near to reality as possible, the availability of detailed and geographically precise data is of major importance.

It is therefore recommendable to make use of the possibility to produce open source software and data sets. This would support every researcher to gain knowledge and help others to make the right choices on energy related topics.

The presented workarounds may help to assume future electricity demands and supply as well as electro mobility charging station capabilities, and the placing of such. It nevertheless stays to be a (valid) workaround. With the above explained need for data to achieve an ideal data world, one would be able to more precisely model and calculate all of the above mentioned topics and provide better data, results and policy recommendations to interested parties.

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