Final Report:
Intermittent renewable resources

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1. Introduction

In energy system models renewable energy carriers require a more detailed examination than conventional energy carriers. Besides the necessary land surface to harvest or utilise renewable energy carriers also the high temporal fluctuations of RES availability raise a specific challenge in implementing renewable energy carriers in the current energy system. On the global scale especially balancing effects due to a timeshift between different world regions may have a major impact. With the current EFDA TIMES model approach this can only be considered insufficiently. Therefore in the actual task an additional approach is utilized to focus more on this specific topic. The TASES (Time And Space reSolved Energy Simulation) model approach is applied to highlight spatial and temporal relations raising from a high penetration of the global energy system by renewable (especially solar and wind) energy carriers.

2. EFDA TIMES model design

The EFDA World TIMES Model is a global multi-regional bottom-up energy system model. It is designed as a partial equilibrium model and distinguishes 15 world regions. The model considers processes and commodities to describe and model the global energy system. Figure 2.1 illustrates processes and commodities considered in the model in a simplified manner.

![Figure 2.1 Simplified illustration of the Reference Energy System RES (Source: Mühlich, 2008)](image)

The objective of the model is the description of the future development of the global energy system by implementing a forecast methodology. Although the model comprises the whole range of energy related process chains and commodities, a special focus is dedicated on a possible future market entrance of fusion power. Besides of fossil and nuclear resources also renewable energy resources are considered in the model. Renewable energy carriers (namely solar energy and wind power) show a high
temporal variation in availability. That faces the overall energy system with significant challenges regarding storage facilities, grid infrastructure and demand side management. This can not be mapped in the current EFDA TIMES framework in an adequate way. Therefore a new model approach is used to tackle these specific characteristics of renewable energy carriers.

3. The TASES model design

The “Time And Space reSolved Energy Simulation – TASES” model has been developed to especially address the impact of high temporal variable and spatial disperse energy potentials in a globally linked energy system. In opposite to the TIMES model approach it is not designed as a foresight model that describes the future development of the energy system, but as a snap-shot model that outlines the optimal energy system setup under specific conditions.

The TASES concept aims at collecting and visualising energy relevant parameters in their temporal and spatial dimensions using methods of geoinformatics. This refers to fluctuations within the availability of renewable energy potentials due to the time of the day or the season (e.g. solar insolation, wind speed, etc.) on the one hand and the load curve of the energy consumers at different areas on the other hand. Based on this temporally and spatially disaggregated energy flows are simulated with the TASES concept.

By the inclusion of all time-critical factors of an energy system and their spatial localization, the TASES approach allows the exemplary visualisation of temporally and spatially correlating events by the development of energy scenarios. Hence TASES offers the basis for the temporally and spatially disaggregated acquisition of relevant energy flows. This feature allows multiple – even competitive - examinations of various energy technologies and their optimum locations of use. The concept TASES is not linked to a predefined spatial scale, but rather allows a highly disaggregated assessment of any energy system. This especially allows for the evaluation of different energy scenarios regarding their practicability. Therefore TASES is appropriate to include the load profile for single components of the energy system into a supra-regional strategic planning processes.

4. Database

4.1. Implementation

The geographic database intended to be utilized for the TASES modeling task must deal with renewable energy carriers with a high spatial data resolution due to the strong relation between available potentials and geography, as well as a high time resolution due to the associated highly fluctuating temporal availability (day/night, seasonal, etc.).

These two parallel considerations increase the size of the database tremendously. To face this challenge and to take into account the varying significance between spatial and time
related dependency of different energy forms, the following way of administrating spatial and temporally disaggregated datasets is supported.

In the case a high time resolution is requested, single ASCII time series - each one describing a geographical location - are supported, which can be accessed via a raster layer data set serving as address structure (see figure 4.1).

\[ \text{Figure 4.1: Administration of temporal and spatial disaggregated datasets. A raster layer dataset links to single time series.} \]

4.2. Data acquisition

In order to get good and reliable modeling results, it is crucial to have reasonable input data sets. The quality of the input database determines the possibilities and the quality of results of the modeling framework. In the modeling framework a first case study is intended to be carried out in order to model the coexistence between renewable energy sources and future fusion power. In a simplified case study, renewable energy sources of solar power, wind power and hydro power will be considered to exist in junction with fusion power in order to meet increasing future global energy demands. In this context, a possible scenario setup is strongly dependent on the geographical relations with regard to solar radiation, wind velocities and hydro power potentials.

Consequently, the main focus in acquiring data for this study is centered on getting proper geographical datasets for solar radiation, wind velocities and hydro power.

All other datasets in that context show a weaker dependency on geographical relations.

**Solar power**

In the case of solar radiation data from NASA (2002) are used (see figure 4.2). NASA data on solar radiation are derived primarily from satellite measurements. Total (integrated) daily solar insolation on a horizontal surface at each degree of longitude and latitude is available for the decade June 1983 to July 1993.

The daily information on solar insolation from NASA can be used to generate daily load curves considering the location specific course of the sun, as shown in figure 4.3. The left-hand side diagram shows the geometric dependencies at play and the right-hand diagram shows the result of applying these dependencies to a daily value. Secondary effects, such as cloudiness, are ignored for the purposes of this transformation.
Figure 4.1 Global solar radiation values from the NASA website. For each location, the total (integrated) daily insolation on a horizontal surface is given.

Figure 4.3: Daily solar insolation information can be disaggregated by the knowledge of the geometric relations.

The following derivation shows how the geographical dependencies enter into place. The solar insolation on a horizontal surface can be estimated by calculating the normal component of the insolation vector related to this surface. This component is defined by the following relation:

\[
\cos \Psi = \sin \beta \sin \delta + \cos \beta \cos t^* \quad (1)
\]

where \(\beta\) defines the latitude and \(\delta\) the declination of the sun relative to the Earth. The time dependency is included in the angle \(t^*\). This angle is defined as:

\[
t^* = \alpha + GMT \ (15^\circ / h) \quad (2)
\]

\(t^*\) captures information about the longitude \(\alpha\) and the time shift relative to GMT (Greenwich Mean Time). Equations (1) and (2) allow the daily insolation values to be decomposed into hourly time series.

The time resolution chosen in this study was hours for one year and therefore creating 8760 values. The geographic resolution considered was 1 degree in longitude and latitude (see figure 4.4).
Figure 4.4: Solar database delivers average solar insulation values in W/m² for every 1 degree in latitude and longitude for each hour for the whole globe.

Although the range of available data is restricted to the decade from June 1983 to July 1993, it was assumed that geographic relations would remain stable in the future.

Wind power

For wind the key dataset was the geographic distribution of wind velocities from World Wind Atlas (WWA) (Sander & Partner GmbH, 2002) shown in figure 4.5.

Figure 4.5: The World Wind Atlas delivers 6 hour average wind velocities for each 2.5 degree in latitude and longitude for the complete landmass.

The dataset provides wind speed values for landmass sites with a grid distance of 2.5 degree in longitude and latitude. The temporal resolution is provided by 6 hour wind speed values for the time horizon from 1992 to 2001 at 50 m above ground.
Figure 4.7: Wind database delivers average wind speed values in m/s for every 2.5 degree in latitude and longitude for each 6 hours for the complete global landmass.

Based on this average wind speed, a potential energy harvest is estimated utilizing the load characteristic of a wind power installation with a specific capacity of 400W/sqm.

Figure 4.8: Wind power curve for a specific power capacity of 400W/sqm.

Certainly, this estimation pays no attention to wind speed fluctuation within this 6 hour average values. Normally, wind speed does not stay stable within this time range but follow a Weibull distribution. The influence of this distribution on the real energy output of a wind turbine is quite a complex relation which is discussed in detail in especially dedicated literature, for instance in Allnoch et al (1996).

Due to the already large data volume, this detail has been neglected in respect to the assumption that the cumulated energy harvest out of wind power on the complete globe, with respect to the also rough geographic resolution (2.5 x 2.5 degree), will be satisfactorily processed by the mentioned modeling approach.
Electricity demand

Besides the datasets describing the geographical and temporal disperse potentials of solar- and wind power also electricity demand has been modelled. Since no dataset is available that describes the global distribution of electricity demand with a high spatial and temporal resolution an indicator based approach has to be stressed. Therefore the NASA dataset on earth city lights at night has been utilized to identify the spatial distribution of global electricity demand.

![Figure 4.9: global luminescence at night (Source: NASA)](image)

The interpretation of this dataset (in terms of colour coding) enables the relative comparison of single locations (individual grid cells) regarding the assigned electricity demand (see figure 4.9).

![Figure 4.10: Estimated relative electricity demand, based on the global luminescence as indicator.](image)

The resulting spatial dataset is scaled to regionally aggregated assumptions on the electricity demand derived from the EFDA TIMES model. Therefore for each 2.5° grid cell a synthetic electricity demand has been derived based on the visual interpretation of figure 4.9 and a normalisation to global aggregated assumptions on the electricity demand (see figure 4.10). Electricity demand load curves for the individual grid cells are generated synthetically by utilizing the demand load pattern of the UCTE grid (see figure 4.11)
Due to the fact that no electricity load pattern for other world regions has been available a rough approximation of electricity demand load pattern at different locations has been made. It has been assumed that the load pattern in each single location is similar – beside the time-shift – to the load pattern in the UCTE grid. Therefore in each single grid cell this load pattern has been shifted due to the longitude of the location and due to the seasonal abbreviation between northern- and southern hemisphere. That reflects not the real situation but is assumed of a rough approximation to real demand load pattern.

5. Regional intermittent Supply/Demand curves

The market share of renewable energy sources is not at least triggered by the ability to match the demand load curve in a certain region. This ability can be investigated by considering load-duration curves for the temporally variable renewable energy supply and balance them with the demand load curve. This enables a better estimation of a possible market penetration by temporal fluctuative energy sources. Therefore in a separate calculation – not part of TASES model runs – some scenarios have been investigated. In these scenarios especially the possible demand coverage by PV and wind power has been investigated.
Sorted load duration curves for renewable energy supply, demand and especially for the balance between supply and demand provides a good basis to evaluate the ability of temporally variable renewable energy carriers to satisfy the request on-demand (see figure 5.1). The evaluation of these load duration curves and in particular the balance curve enables the calculation which share of the electricity demand load curve in one certain region could be satisfied in real-time by variable solar- and wind potential curves WITHOUT any grid connection to neighbouring regions or storage facilities.

Table 5.1 shows the possible coverage of electricity demand in the EFDA TIMES regions by solar- and wind power installations in relative numbers. It is assumed, that solar- and wind power installations will be installed equally distributed over the whole region in order to profit best from balancing factors due to location- and time-shifts. To be able to analyse the influence of different installation levels different balance calculations are outlined. Three different categories are distinguished:

- demand exclusively covered by solar PV
- demand exclusively covered by wind power
- demand covered by solar PV and wind power

Figure 5.1: Load duration curves for intermittent supply and demand.
Table 5.1: Possible demand coverage in % by solar- and wind power for different levels of solar (red) and wind (blue) power installations in the EFDA TIMES regions.

<table>
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<th>FSU</th>
<th>EEU</th>
<th>WEU</th>
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<td>67%</td>
<td>24%</td>
<td>44%</td>
<td>67%</td>
<td>56%</td>
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</tbody>
</table>
Balance calculation PV:
In the first case only solar power potential is considered to cover the electricity demand. The calculations consider solar power installations relative to the whole region area varying by a factor of 100 and more. It figures out that with low solar power installations relative to the entire area of one region only AFR and AUS can (due to available area and solar insolation values) cover a significant share of the electricity demand without storage facilities and grid connection to other regions. Raising the installed solar collector installations by a factor of 100 and more leads to following awareness:
Demand load can be covered only up to a level of 50 % to 60 % and than it is saturating due to the availability gap of solar power during night. Only regions with a high infrastructure and population density (like JPN or WEU) are not reaching a share beyond 20 % (see figure 5.2).

![Figure 5.2: Possible demand coverage depending on solar installations relative to region area.](image)

Balance calculation Wind:
In this calculation only wind power is considered to satisfy the demand load. Since average wind speed over time do not show any systematic gaps like solar insolation during night and (also no significant seasonal pattern are shown) it is easier with wind power to satisfy – even on a decoupled regional scale – the demand load curve. From a statistical point of view also a 100 % saturation of electricity demand by wind power alone can be reached. The considered wind power installations in the individual calculations vary by a factor of 30.
Balance calculation – PV/CSP and wind:
The combination of both potentials (solar and wind) to satisfy the demand load curve on the regional scale combines the advantages of time pattern from solar potentials and wind potentials. At low installation levels their share in the demand satisfaction can be considered as additive. At higher installation levels the demand satisfaction is mainly triggered by wind power installations.

All in all table 5.1 outlines a quantification of possible shares in the electricity demand covered by regional solar- and wind power potentials WITHOUT storage facilities to balance supply gaps.
The possible impact of available storage facilities or interregional grid connections to balance the temporal availability variations of renewable energy supply is challenging and therefore needs new model approaches. The TASES model framework has been developed to tackle exactly this question. In the next chapter a preliminary scenario set is presented, that demonstrates this issue in a very simplified manner.

6. TASES scenario runs

In this section scenarios are presented and discussed which address the possible share and regional distribution of solar power and wind power facilities. Relevant grid infrastructure, storage capacities and back-up power is also regarded.

In order to reduce the model size the considered time pattern for grid cells in single model runs has been restricted to 3-hour steps in 4 type days reflecting the daily demand and supply pattern.
That accumulates to 32 considered time steps in the model run. It has been chosen as compromise between acceptable computation time and accuracy in reflecting spatial and temporal correlations regarding demand coverage by intermittent renewable resources.

A scenario set has been performed which consider only solar power, wind power, storage infrastructure, grid infrastructure and back-up power available to satisfy the electricity demand (see figure 6.2)

The parameterisation of the individual processes/technologies is in a first step restricted to investment costs, fuel costs and efficiencies. Additionally also restriction regarding the utilizable area are considered. Table 6.1 outlines the assumptions made for the base scenario.

Table 6.1: Considered technologies and describing parameters (Biberacher, M. (2006)).

<table>
<thead>
<tr>
<th>Technology</th>
<th>Investment costs</th>
<th>Efficiency</th>
<th>Fuel costs</th>
<th>Restrictions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar power PV</td>
<td>8,72 € /sqm/year</td>
<td>22 %</td>
<td>-</td>
<td>0.1 % of surface</td>
</tr>
<tr>
<td>Wind power*</td>
<td>37,0 € /sqm/year</td>
<td>100 %</td>
<td>-</td>
<td>0.1 % of surface</td>
</tr>
<tr>
<td>Storage</td>
<td>75,0 € / kWh / year</td>
<td>90 %</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Grid infrastructure</td>
<td>6e-05 € / (kW<em>km</em>year)</td>
<td>99,997 % / km</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Back-up technology**</td>
<td>185 € / kW / year</td>
<td>100 %</td>
<td>0,05 €/kWh</td>
<td>-</td>
</tr>
</tbody>
</table>

* per sqm rotor surface; ** per kW elec. output

The framework enables a sensitivity analysis of scenarios regarding the impact of chances in the parameter set on the optimal system setup. Especially the impact triggered by spatial and temporal influences can be investigated.

Figure 6.2 shows the impact triggered by changes in the investment costs of solar power installations within the EFDA world regions. Scenario 1 assumes a reduction of the investment costs for solar power installations to 4,74 € / sqm /year and scenario 2 optimises the energy system using investment costs for solar power of 2,37 € / sqm /year.
The outlined scenarios reflect the ability of the model framework. In figure 6.3 the aggregation of the scenarios to the single EFDA model regions is shown. With the assumptions of the base scenario no solar power is installed in the EFDA world regions. What is obvious in the scenario is the fact that solar power would generally be most favourable in
the sun-belt of the globe, especially with lower investment costs of solar power. Therefore especially AFR, CSA, IND, MEA, MEX and ODA would be the favoured regions for solar power installations in scenario 1 and 2.

**Figure 6.3: Model results aggregated to EFDA model regions.**
Optimal wind power installations are not really impacted by increasing solar power installations. Needed storage facilities to balance intermittent resources are highly sensible to the overall system setup. A general decrease of storage capacities with rising solar installations on a global level could be also accompanied by rising storage installations in certain regions (for the current scenario set in CSA for instance). Backup capacity is mainly needed in regions with high energy demand and restricted renewable energy potentials (also in terms of available area).

Next to aggregated supply installations also cumulated transport capacities between regions are investigated (outlined in figure 6.4). Transport capacities are calculated in the model by considering balance flows from on grid cell to neighbouring grid cells in each single time step. The maximum value of balance flows over all time steps between each two neighbouring grid cells defines the transport capacity (see figure 6.2).

*Figure 6.4: Transfer capacities between neighbouring regions for the outlined scenarios.*
Figure 6.4 outlines the resulting grid capacities between the single EFDA model regions which are needed to satisfy the scenario constraints. For the “Base Scenario” the real transport capacities are outlined and for the scenarios “1” and “2” the difference to the “Base Scenario” is outlined.
What can be observed from the evaluation is, that with increasing solar power installations the transport capacities especially from AFR to neighbouring regions increases tremendously relative to the “Base Scenario”.

7. Conclusion and Outlook

In the current task the TASES model framework has been made available in order to investigate the impacts triggered by renewable energy resources with high temporal availability variations. The framework has been adapted to the EFDA model approach and first scenario runs have been carried out.
This framework in general enables the investigation in sensibility aspects regarding high intermittent demand and supply pattern on a global scale. In the EFDA TIMES model these relations are covered very purely – not at least triggered by the linear approach that enforces always a certain simplification. With the TASES model framework snap shot scenarios can be investigated which give a feedback on relevant constraints in terms of transport capacities or optimal power plant locations in the context of a global energy system.
In the next tasks the model approach will be applied to investigate specific sensibilities triggered by temporally variable resource potentials in order to adjust the EFDA TIMES global model. Therefore the intention is, to implement the share of intermittent renewable energy carriers will by endogenous relations in the EFDA TIMES model in order to better build up the impact, challenges and chances of intermittent renewable energy carriers in a global energy system.
8. Literature


