Modelling the capacity credit of renewable energy sources

Power generation from renewable resources such as wind and solar power varies from hour to hour according to prevailing weather conditions. This is different to fossil-fuel generators, which can normally be dispatched according to their operators' preferences (which, in a competitive market, means that they can choose to generate when spot prices are sufficiently high).

As the penetration of variable renewable generation technologies increases, the variable nature of their output will become a more important feature of power systems. In particular, it will have an impact on the amount of capacity that needs to be installed to meet peak system demand, and on the operating patterns of other generators.

This document describes how the fundamental variability of some renewable energy sources was taken into account in the World Energy Model (WEM). This analysis was used both to calculate the "capacity credit" of variable renewables and therefore the additional capacity required as a result of variable renewables[1] (see discussion in Chapter 5 of the *World Energy Outlook 2011*). It was also used in the general modelling of the power sector in the scenarios discussed throughout the *Outlook*.

1.1 Defining load-duration curve

The instantaneous demand for electricity in any market varies continuously. Because supply must exactly meet demand at all times in a power system in order to maintain the system's stability, this means that generation also ramps up and down continuously in line with demand.

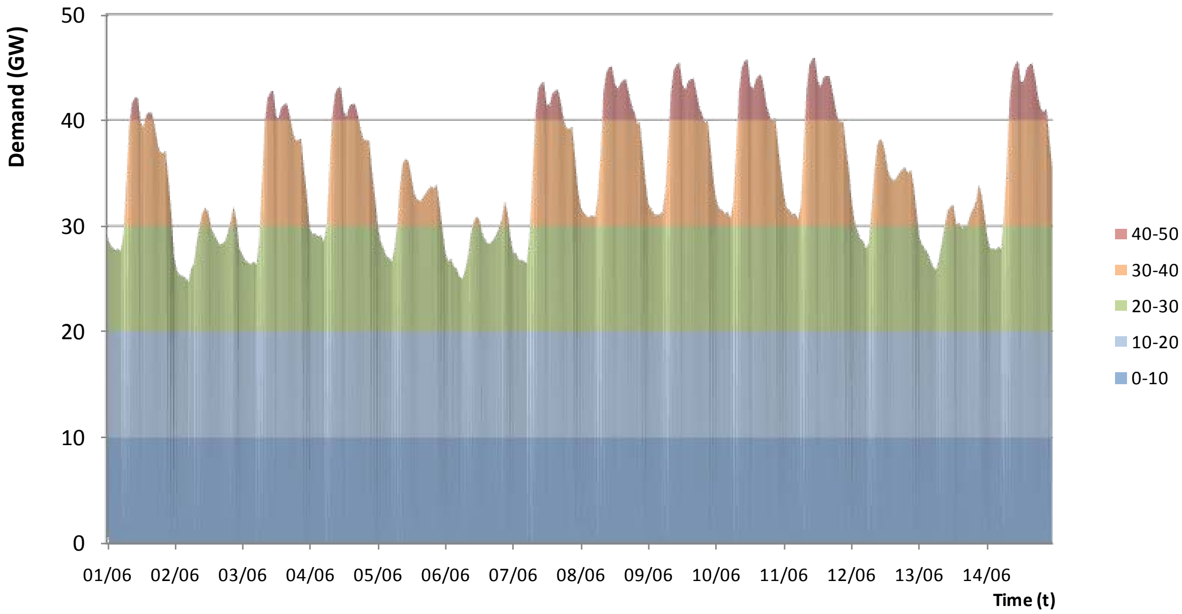
To examine a power system's pattern of generation and demand over a year, it is possible to define a function $Load(t)$ that expresses the instantaneous demand (or load) in a power system at time t. From $Load(t)$ it is possible to derive a "load-duration" function, which shows the cumulative amount of time for which demand exceeds a certain level.

$$LDC(t') = sort[Load(t)]$$

As an illustrative example, Figure 1 shows electricity demand in Italy during the first two weeks of June 2010. It can be seen that there is a strong daily pattern of demand, with the highest demand during the day and lower demand in the nights, and a visible weekly pattern, with lower demand on weekends (5/6-6/6 and 12/6-13/6) as well as on 2/6 which was a public holiday. Figure 2 shows the load-duration curve for the same period. This was constructed by taking the same data as is shown in Figure 1 and rearranging it in order of demand.

[1] The term "variable renewables" refers to the following non-dispatchable generation technologies: Wind Onshore, Wind Offshore, Solar PV, Solar CSP without storage, Tidal and Wave. We assume that other generators, including Hydro, Bioenergy, Geothermal, Solar CSP with storage and CHP power plants do not fall under the category of "variable renewables". In practice, the distinction is not completely unambiguous: for example, some tidal generation technologies that are currently proposed or under development would be dispatchable; some hydroelectric installations are not fully dispatchable.

Figure 1 – Electricity demand in Italy, first two weeks of June 2010



Original data from Gestore Mercati Energetici (www.mercatoelettrico.org), retrieved 3 November 2011

Figure 2 – Load duration curve for Italy, first two weeks of June 2010

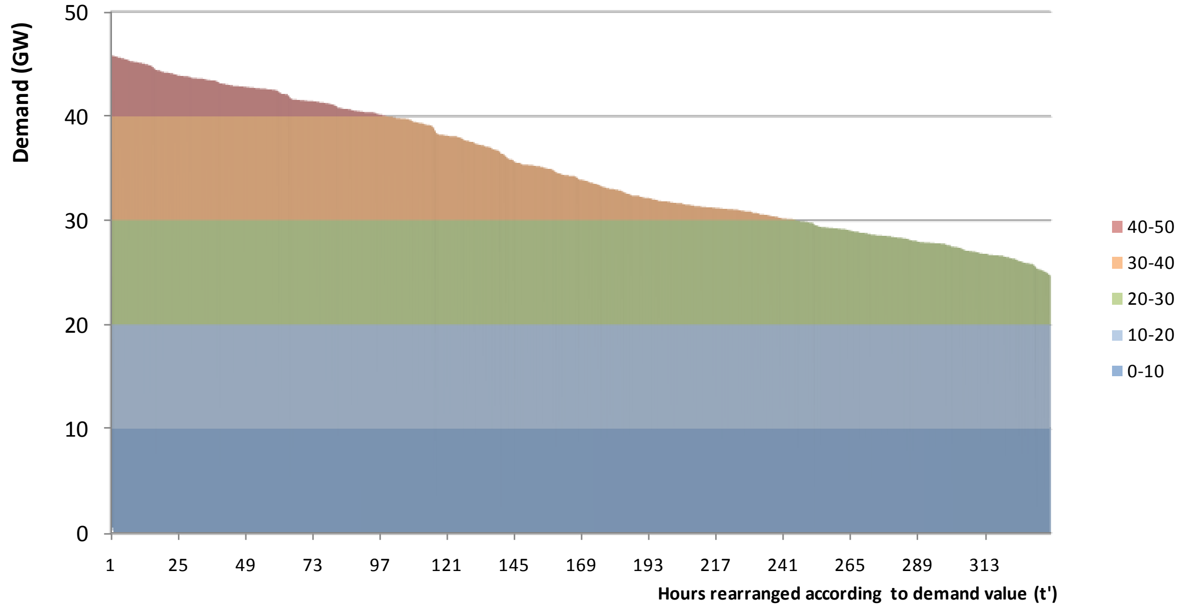
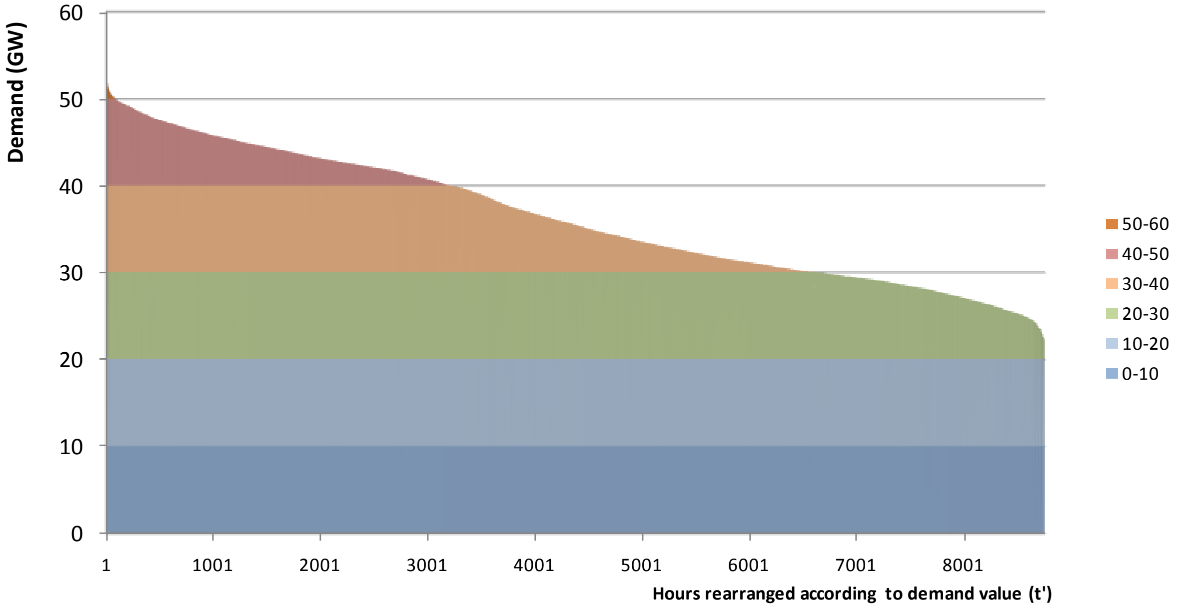


Figure 3 shows the load-duration curve for Italy for the whole of 2010. It can be seen that demand never falls below 22GW, and that demand sometimes reaches over 50GW, but only for a very small number of hours a year (around 90 hours or 1% of the time). Even though demand is at this level for only a small number of periods, the need to balance supply and demand at all times implies that a little over 50GW of generating capacity must be installed and available at the time of system peak in order to ensure security of supply.[2]

[2] In fact, more than 50GW will need to be installed because technical failures mean that not all generators can be expected to be available at all times. Well-functioning power systems therefore have a higher amount of generating capacity than the expected peak demand: this capacity margin exists to ensure security of supply.

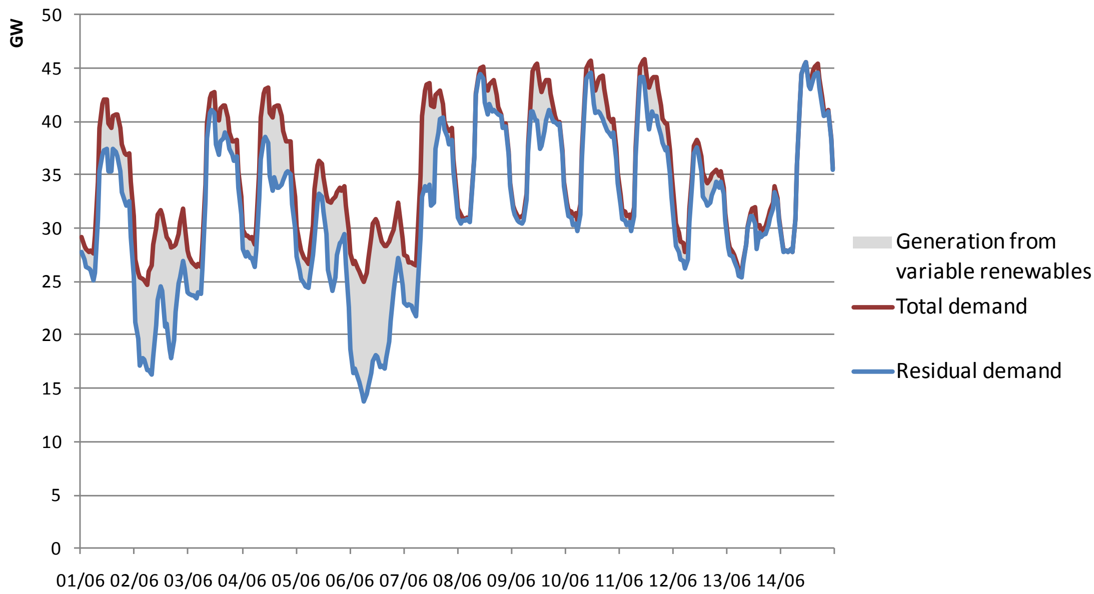
Figure 3 – Load-duration curve for Italy for all of 2010



1.2 Deriving a residual load-duration curve

In the presence of variable renewable generators, generation from other sources (such as hydro, fossil fuels, and nuclear) must meet any demand that is not fulfilled by the variable generation. Figure 4 shows the same demand pattern as was shown in Figure 1, along with a simulated time series of variable generation for the same period.[3] The residual demand line represents the demand that must be met by non-variable generators.

Figure 4 – Electricity demand and example residual electricity demand in Italy, first two weeks of June 2010



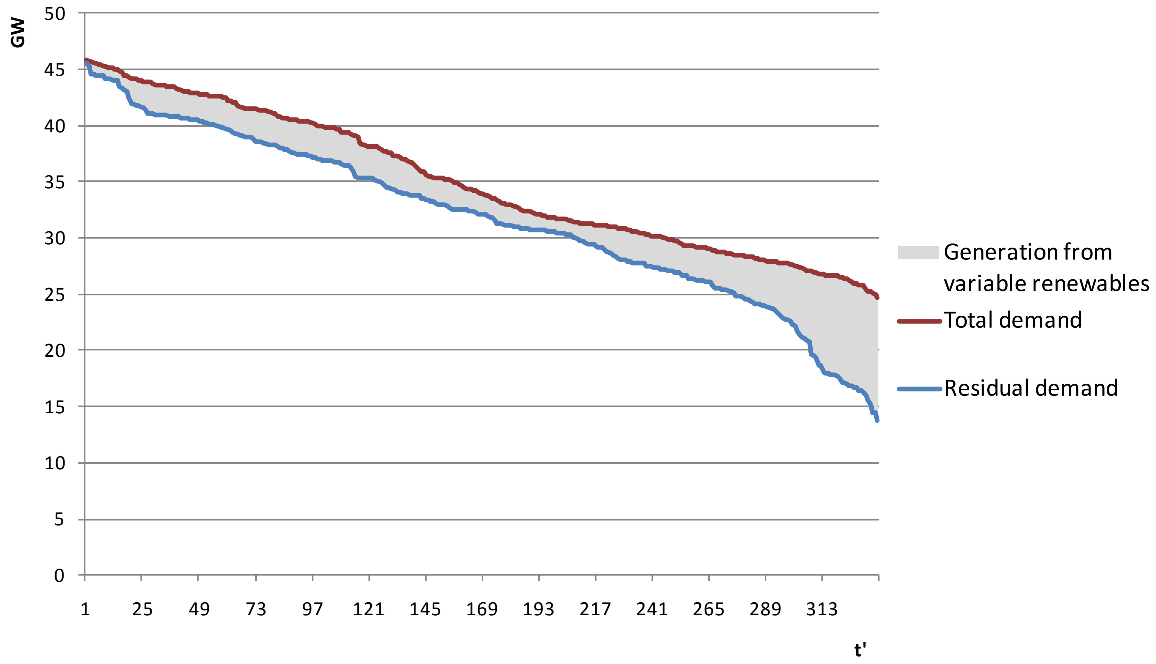
[3] Please note that this has been scaled for illustrative purposes: the demand is the same pattern as shown in Figure 1 but the generation from variable renewables is an example that that is not based on historical data.

In the same way as it is possible to define a load-duration curve for total demand, it is possible to define a residual load-duration curve $ResLDC(t')$, for residual demand:

$$ResLDC(t') = sort[Load(t) - Generation_{RES}(t)]$$

Figure 5 shows the load curve and residual load curve for the data shown in Figure 4. (Again, note that the variable renewable generation data is an example). The grey area between the two curves represents load that is fulfilled by generation from variable renewables; energy below the blue line must be satisfied by other sources of generation.

Figure 5 - Load-duration curve and example residual load-duration curve for Italy, first two weeks of June 2010



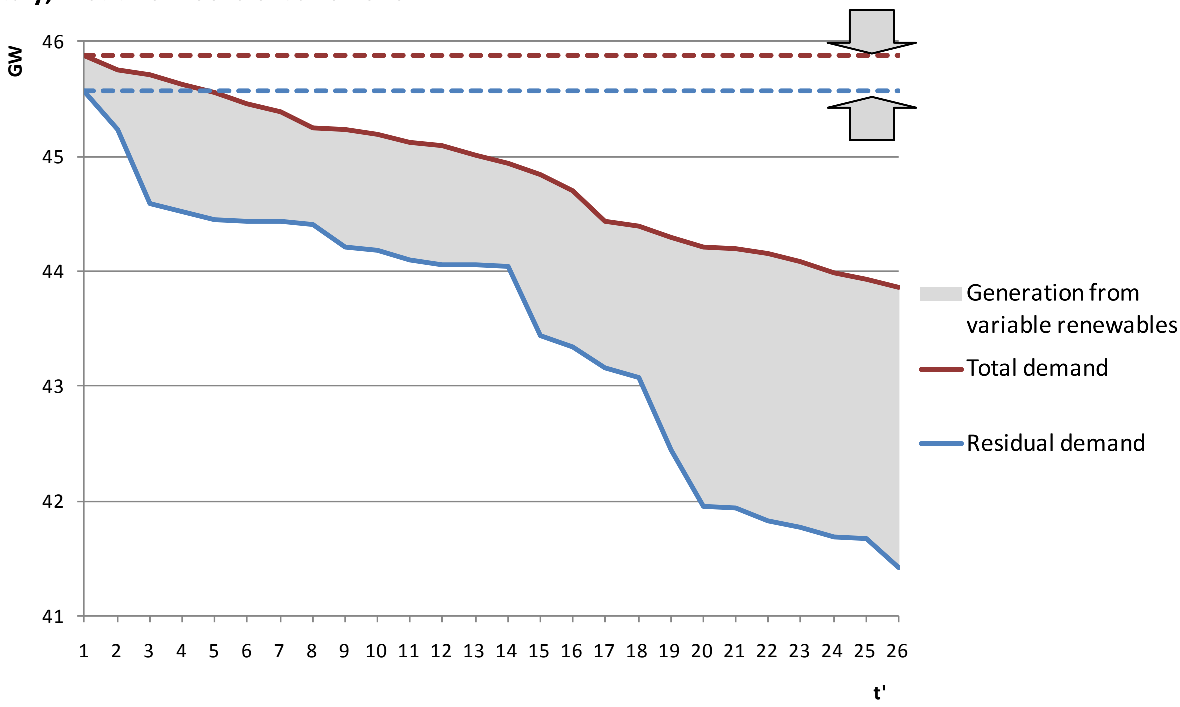
1.3 Defining capacity credit

Figure 6 shows a highly-magnified section of the load-duration and example residual load-duration curve shown in Figure 5. It can be seen that there is a difference between the peak demand and the peak residual demand, which is shown by the dotted lines and the grey arrows. This difference between the peak of the load-duration curve and the residual load-duration curve represents generation capacity that is not required due to the presence of variable renewables, during the period in question (the first two weeks in June 2010).

By considering an extended time period spanning many years rather two weeks, it is possible to evaluate how much capacity is replaced by variable renewables by looking at the difference between the peak demand and the peak residual demand. This is the idea underlies the concept of capacity credit.

The capacity credit is the peak demand less the peak residual demand, expressed as a percentage of the variable renewables installed. For example, if 10 GW of wind power plants are installed in a region, and their capacity credit is 10%, then the there will be a reduction of 1 GW in the amount of other plants required, compared to a situation with no wind capacity.

Figure 6 - Magnified section of load-duration curve and example residual load-duration curve for Italy, first two weeks of June 2010



Expressed algebraically, the capacity credit can be described as:

$$CC_{peak} = \frac{Reduction\ Capacity_{Thermal}}{Capacity_{VarRES}}$$

$$= \frac{\max_t\big(Load(t)\big) - \max_t\big(ResLoad(t)\big)}{Capacity_{VarRES}}$$

$$= \frac{LDC(t' = 1) - \ ResLDC(t' = 1)}{Capacity_{VarRES}}$$

where $LDC(t')$ is the load duration curve, $ResLDC(t')$ is the residual load duration curve, and $Capacity_{VarRES}$ is the installed capacity of variable renewables.

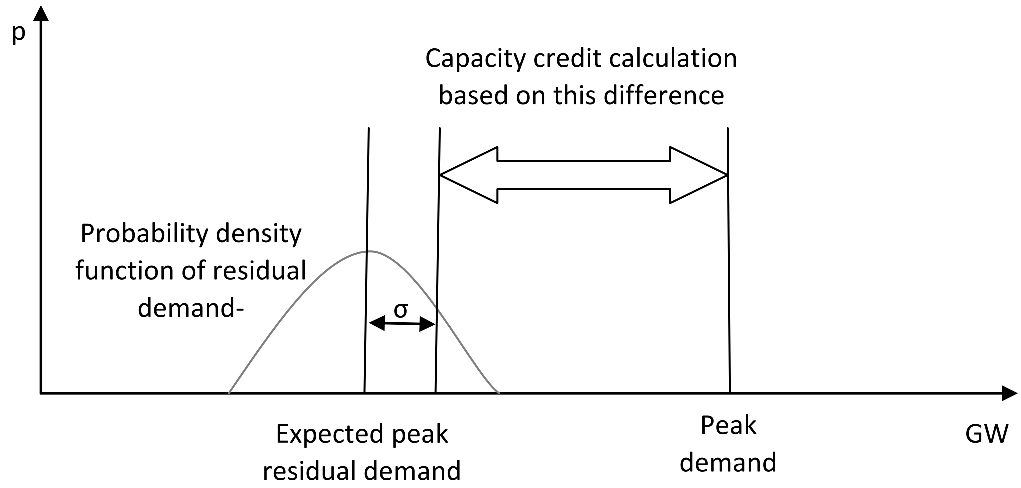
1.4 Calculating capacity credit

In order to calculate capacity credit for the purposes of the analysis in *WEO-2011*, meteorological data (wind speed and solar insolation) for several years in a number of regions was combined this with typical production profiles of wind and solar PV generators. This yielded regional generation patterns for variable renewables. Hourly demand profiles for the same regions over the same time periods and were then used to create load-duration curves and residual load-duration curves for each of the years where data was available. The analysis was restricted to regions where data was available (principally Europe and the United States). The analysis was also limited to wind and solar PV as they are the most significant forms of variable generation in the *World Energy Outlook* projections.

From this data it was possible to calculate the annual peak demand and annual residual demand in each region.

Because of the considerable variation in variable renewables output from year to year, it was assumed that the annual peak residual demand is normally-distributed and calculated the capacity credit based on the difference between peak demand and the point one standard deviation above the residual peak demand (Figure 7).

Figure 7 – Assumed probability distribution used as the basis for calculation of capacity credit



By comparing the capacity credit of renewables with the capacity credit of thermal plants delivering the equivalent volume of energy, it is possible to estimate the additional capacity required in order to maintain system adequacy in the presence of variable renewables. This figure is presented and discussed in Chapter 5 of *World Energy Outlook 2011* (pages 190-193).