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INTERMITTENT RENEWABLES, THERMAL POWER AND HYDROPOWER - COMPLEMENTS OR COMPETITORS?

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INTRODUCTION

Around 80% of the electricity demand in the world is still supplied by fossil fuelled power or nuclear, i.e. thermal generation. Wind and solar power is integrated into the electricity generation systems to decrease the amount of carbon dioxide emissions associated with the generation of electricity as well as to enhance security of supply. Wind and solar power plants differ from thermal generation in two important ways: they have very low running costs (and high capital costs) and a generation level that depends on external elements. Due to the low running costs there are strong economic incentives for the employment of wind and solar power to supply the electricity demand once the capacity has been put in place. However, the share of the load that can be supplied by wind and solar power in a certain hour or second varies irregularly since it depends on prevailing wind speeds, solar irradiation and cloudiness.

Thermal units are most efficiently run continuously at rated power. However, in a mixed renewable-thermal system they may have to compensate for fluctuations in wind and solar generation. Thus, depending on the characteristics of the renewable-thermal system, part of the decrease in fuel costs and emissions realised by wind and solar power may be offset by a reduced efficiency in the operation of the thermal plants. This chapter discusses the interaction between intermittent renewable power and thermal power, and investigates briefly the impact of including a more controllable renewable source such as hydropower in these mixed systems.[1]

THE OPERATION OF A THERMAL POWER SYSTEM – MEETING VARIATIONS IN LOAD

The electricity generation system is designed to meet the load at any instant in time. The demand for electricity generally varies in a regular pattern between night and day, workday and weekend, season to season (Figure 11.1). In a thermal system, the demand which remain throughout the week is typically met by thermal units deigned for continuous power production. These units have low running costs at rated power, but poor part load properties and high start-up costs. We will refer to them as base load units. The additional demand during day-time is met by thermal units with higher running costs but better part load properties and lower start-up costs, i.e. peak load units.

In each power system there is a balance between base load and peak load capacity to match the load variations of that specific system. Since load variations follow a regular diurnal pattern it is fairly well known when and to what extent different plants need to be in operation.

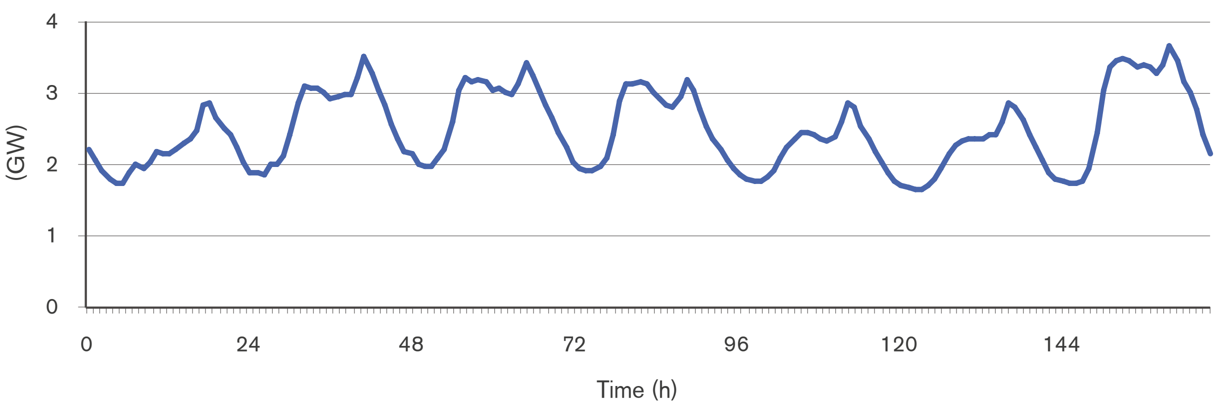

Figure 11.1. Total hourly load in western Denmark the first week in January 2013. Source: Energinet (2013)

A reduction in load or an increase in wind and solar power generation in a renewable-thermal power system that uses no active strategy for variation management (i.e. storage or demand side management, see Chapter 5, 9, 10 and 12) can be managed (passively) in three different ways: part load operation of thermal units, stopping thermal units, or curtailing power from renewable units.

The choice of variation management strategy depends on the properties of the thermal units which are in operation and the duration of the variation. In a power system where the total system cost to meet the load is minimised, the variation management strategy associated with the lowest cost is chosen. If, for example, the output of wind power and some large base load unit exceeds demand for one

1 See Chapters 3 and 4 on the characteristics and availability of different renewable energy flows.

hour, curtailment of wind power, or possibly some curtailment in combination with part load of the thermal unit, might be the solution associated with the lowest total system cost. If the same situation lasts for half a day, stopping the thermal unit might be preferable.

Three properties of thermal units will have an immediate impact on the scheduling of the units: the minimum load level, the start-up time and the start-up cost. The start-up time is either measured as the time it takes to warm up a unit before it reaches a state where electricity can be delivered to the grid (called 'time until synchronisation') or as the time before it delivers at rated power ('time until full production'). In both cases, the start-up time ultimately depends on the capacity of the unit, the power plant technology and the time during which the unit has been idle. Small gas turbines have relatively short start-up times, in the range of 15 minutes (time until synchronisation), and large steam turbines have long start-up times, in the range of several hours (up to three days for supercritical coal, see Table 11.1). If a large unit has been idle only for a few hours, materials might still be warm and the start-up time can be reduced.

The costs associated with starting a thermal unit are a result of the cost of the fuel required during the warm-up phase and the accelerated component aging due to the stresses on the plant from temperature changes.[2] Intertek Aptech have summarised cycling costs of thermal units in the US for NREL[3]. A summary of their lower bound costs can be found in Table 11.1.

Table 11.1 Typical cycling costs of thermal units in the US in operation in 2012. Source: Kumar, N. et al. (2012).

	Hot start [EUR/MW]	Warm start [EUR/MW]	Cold start [EUR/MW]	Startup time [h]
COAL				
Super critical	30	40	70	12 - 72
Large sub critical	30	50	70	12 - 40
Small sub critical	40	70	70	4 - 24
GAS				
Combined Cycle	20	30	50	5 - 40
Steam	20	30	40	4 - 48
Large Frame CT	20	20	30	2 - 3
Areo Derivative CT	10	10	10	0 - 1

[a] USD is converted to EUR with an exchange rate of 0.75.

One alternative to shutting down and restarting a thermal unit is to reduce the load in one or several units. The load reduction in each unit is restricted by the maximum load turn-down ratio. The minimum load level of a thermal unit depends on the power plant technology and the fuel used in combustion units. For example, the minimum load level reported for Danish units range from 20% of rated power for gas- and oil-fired steam power plants to 70% of rated power for waste power

2 It has been shown that the combined effect of creep, due to base load operation, and fatigue, due to cycling (start-up and shutdown and load following operation), can significantly reduce the lifetime of materials commonly used in fossil fuel power plants in comparison to creep alone. Lefton et al. (1995) *Managing utility power plant assets to economically optimize power plant cycling costs, life and reliability*. Sunnyvale, CA, USA: Aptech Engineering Services, Inc.
3 Kumar et al. (2012) *Power Plant Cycling Costs*. Boulder, CO, USA: NREL. (Report NREL/SR-5500-55433).

plants. Minimum load level of coal fired power plants range from 35% to 50% of rated power depending on technology.[4]

A low minimum load level is of great importance for any load following thermal unit since it allows for operation under a wide range of load situations and reduce the need for cycling. Size matters when it comes to cycling properties, because small units have a low minimum load level in absolute terms. It may be possible to find a combination of small units to suit the load situation at hand while only cycling a few of the units, while a large unit would have to choose between shutting down (and later restart) the whole capacity or deliver power at a price below running costs.

Running thermal units at part load is associated with an increase in costs and emissions per generated kWh, since the efficiency decreases with the load level. The rate of the decrease in efficiency depends on the power plant technology and the level to which the load is reduced. The rate of decrease in efficiency is generally lower at high load levels than at low load levels. The efficiency of combined cycle plants (CC) is typically more sensitive to a load level decrease the than the efficiency of steam plants since gas turbines are sensitive to part load operation.

WIND POWER REDUCES THE COMPETITIVENESS OF BASE LOAD UNITS

In contrast to load variations, wind power variations follow no given pattern (compare Figure 11.1 and 11.2). The power output of a single wind turbine can vary rapidly between zero and full production. However, since the power generated by one turbine is small relative to the capacity of a thermal unit, such fluctuations have negligible impact on the generation pattern of the thermal units in the overall system.

With several wind farms in a power system, the total possible variation in power output can add up to capacities corresponding to the thermal units and influence the overall generation pattern. The power output of the aggregated wind power is, however, quite different from the power output of a single turbine. Wind speeds depend on weather patterns as well as the landscape around the wind turbines (i.e. roughness of the ground, sea breeze etc.). The greater the difference is in weather patterns and environmental conditions between the locations of the wind turbines, the lower the correlation in power output.

In a power system with geographically dispersed wind farms, the effect of local environmental conditions on power output will be reduced. Since it takes some time for a weather front to pass a region, the effect of weather patterns will be delayed from one farm to another, and the alteration in aggregated power output thus takes place over a couple of hours rather than instantaneously. This effect is referred to as power smoothing.[5] Western Denmark is a typical example of a region with dispersed wind power generation. The aggregated wind power output for this region during one week in January can be found in Figure 11.2. Variations in the range of the capacity of thermal units do occur. For example, between hour

4 Energinet (2007) *Technical Regulations for Thermal Power Station Units of 1.5 MW and higher.* Frederica, Denmark: Energinet. (TF 3.2.3)

5 Manwell et al. (2005) *Wind energy explained: Theory, Design and Application.* Chichester, UK: John Wiley & Sons, Ltd.

92 and 105 the wind power generation decreases by 2.3 GW. However, this large shift in output power is not instantaneous, but takes place over several hours.

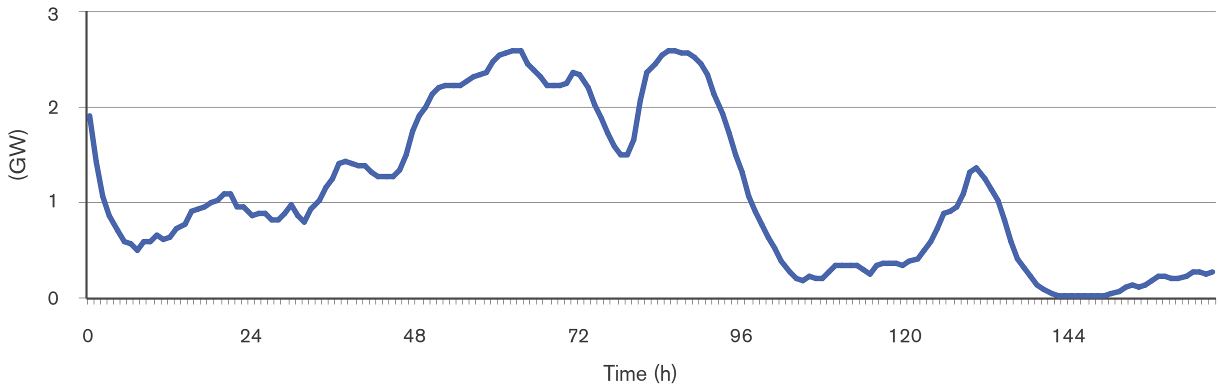

Figure 11.2 Hourly wind power generation in western Denmark during the first week in January 2013. Source Energinet (2013)

For the thermal units, it is the aggregated impact of wind power and the total load which is of importance. On a seasonal basis, there is a positive correlation between wind power generation and load in northern Europe, i.e. it is windier in wintertime when there is a demand for electricity for heating purposes. However, on an hour to hour basis, the correlation between wind power and load is generally low. Maxima and minima of wind power output on the one hand and electricity demand on the other may overlap at any time of the year, resulting in large variations in load on the thermal units. At times when wind power output is high and demand is low, systems with wind power in the range of 20% grid penetration or higher might face situations where power generation exceeds demand. Without storage in the system, some of the wind power generated will then have to be curtailed. With base load capacity with very high start-up costs (Table 11.1), situations where curtailment is preferable will arise more frequently.

Studies using models of the power system of western Denmark suggests that wind power variation influences the relative competitiveness of different thermal power plants.[6] In general, simulations show that an increase in the amount of wind power reduces the duration of periods of constant production. Then units with high start-up costs and high minimum load level (i.e. base load units) will be used less. This result might seem trivial. However, high start-up costs and high minimum load levels are common properties of units with low running costs designed for base load production. Thus, low running costs compete against flexibility and in a system with significant wind power capacity the unit with the lowest running costs is not necessarily the best complement.

As an illustration, Figure 11.3 gives the modelled capacity factors of Enstedtsverket and Fynsverket 2, at different wind penetration levels.[7] The system operation has been scheduled so as to minimise the system running costs while including or omitting start-up costs and minimum load level constraints of the thermal units.

6 Göransson, L. and F. Johnsson (2009) Dispatch modeling of a regional power generation system - Integrating wind power. *Renewable Energy* 34(4):1040-1049

7 The capacity factor measures the utilisation of a power plant, and is calculated as the ratio between the actual annual electricity generation and the maximum annual electricity generation at rated power.

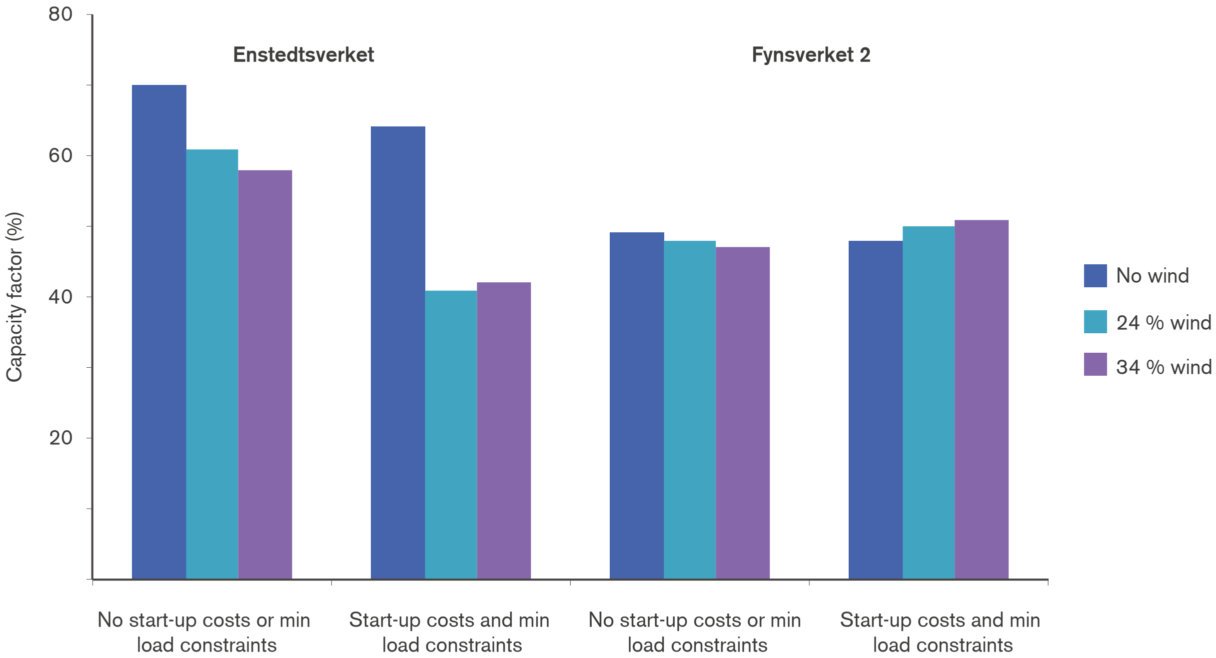

Figure 11.3 Capacity factor of Enstedtsverket and Fynsverket 2 with and without including start-up costs and minimum load level constraints, as wind power supply an increasing share of the demand for electricity.

Enstedtsverket is the single largest thermal unit in the western Denmark system. It has the lowest running costs in the system and if start-up costs and minimum load level constraints are omitted, Enstedtsveket has the highest capacity factor of the thermal units in the system at all wind power penetration levels. However, Enstedsverket also has the highest start-up cost (in absolute terms) and the highest minimum load level. Consequently, Figure 11.3 shows that if start-up costs and minimum load level constraints are included, the capacity factor goes down rapidly in the cases with high wind power penetration.

Fynsverket 2 has higher running costs than Enstedtsverket, but also significantly lower minimum load level. If cycling costs and minimum load level constraints are omitted, the operation of Fynsverket 2 would have been reduced, although to less extent than Enstedsverket due to a lower initial capacity factor. However, if cycling costs and minimum load level constraints are accounted for, the capacity factor of Fynsverket 2 increases as it replaces units with worse cycling properties such as Enstedsverket. The variations in wind power production have thus altered the dispatch order of the thermal units between the no wind and the wind cases, favouring units with more flexible properties over the unit with the lowest running costs.

Several studies have investigated the cost of cycling thermal generation in electricity generation systems with 20% wind power and found that they are small compared to total system cost (i.e. a few percent of the running costs and start-up costs).[8] At this penetration level, cycling costs are also found to be small compared to the reduction in fuel costs realised by the inclusion of wind generation.

8 Göransson, L. and F. Johnsson (2009) Dispatch modeling of a regional power generation system - Integrating wind power. *Renewable Energy* 34(4):1040-1049.; Holttinen et al. (2009) *Design and operation of power systems with large amounts of wind power IEA Wind task 25*, Helsinki, Finland: VVT. (VTT RESEARCH NOTES 2493).; Jordan, G., and Venkataraman, S. (2012) *Analysis of Cycling Costs in Western Wind and Solar Integration Study*. Boulder, CO, USA: NREL

SOLAR POWER REDUCES PEAK LOAD UNIT PRODUCTION HOURS

From an aggregated perspective, solar power generation is highly correlated with demand. High load hours typically occur during daytime when the sun is up and solar power can be generated.[9] In southern Europe and southern US there is even a direct physical relation between solar power and electricity demand; when it is sunny the electric load from air-conditioning is high while solar power delivers at full capacity. In the absence of sun, the electric load from cooling devices is also reduced. Figure 11.4 illustrates the general correlation between the demand for electricity and solar generation for a low voltage grid in Germany.[10]

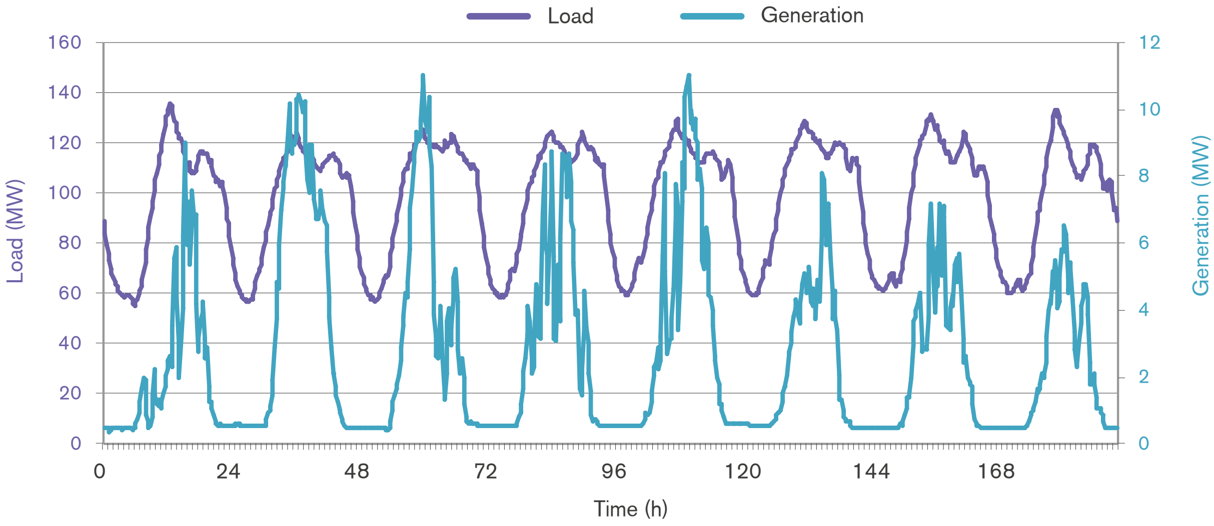

Figure 11.4 Hourly generation (infeed) and load on a low voltage grid in Germany. Source: ENERVIE AssetNetWork GmbH (2013).

During peak load hours, peak load and mid-merit load is in operation as well as base load units. Solar power production will replace the units with the highest running costs first, in this case typically peak load units with good flexible properties. If all units in operation are subject to significant start-up costs, it may suffice to reduce operation in several units to part load operation to accommodate the solar power generated. Solar power can thus be integrated to some extent before it causes start-up costs of any significance.

THE REMAINING NEED FOR CAPACITY

As the amount of wind and solar power increases in the system, the operation hours of thermal units will be reduced. Non-marginal levels of wind and solar power in the system will also affect electricity prices. Since wind and solar power have very low running costs they will cause electricity prices to drop under sunny and windy hours. The combination of reduced operation hours and periodically decreased electricity prices will reduce the returns on investments in technologies with high investment costs, such as nuclear power and large coal-fired power plants. However, in the absence of very large storage capacity, there will still be

9 In a distribution grid supporting only private households the load pattern is typically less correlated with solar power production, with higher demand in mornings and evenings (see Chapter 9).
10 ENERVIE Asset Net Work GmbH (2013) [accessed 2013-05-15]

a need for capacity to supply the load during hours of poor wind and solar conditions. Large interconnected systems and combined investments in wind and solar power reduce the number of hours of low wind and solar power generation, but such hours will still occur. On an energy-only market, where electricity producers are paid based on the amount of energy they deliver to the grid rather than for the capacity which they maintain available for production, hours of low wind and solar power generation will be coupled to high costs of electricity. These hours will bring profit to peak load units and are also likely to stimulate demand side management, or demand response (see Chapter 10) and investment in storage (or possibly fuel production, Chapter 12).

There is an ongoing discussion on whether very large fluctuations in electricity prices will be tolerated by electricity consumers. An alternative would be a capacity market where you are paid for capacity which is kept available to the system and/or a market for energy storage.[11]

HYDROPOWER WITH STORAGE AS A COMPLEMENT TO INTERMITTENT RENEWABLES

Similar to thermal units, electricity generation in hydropower plants with storage are not immediately dependent on weather conditions and can thus meet variations in load and wind and solar power generation. For thermal units there is typically a trade-off between good cycling properties (i.e. low minimum load level, low start-up costs and short start-up time) and low running costs. Unlike thermal units, hydropower plants have low running costs and low cycling costs. Assuming infinite storage, the capacity factor of hydropower will remain unchanged as wind power is integrated in the system until the yearly production of wind and hydro power exceeds the yearly electricity demand of the region and its yearly export capacity. Due to storage limitations, wind and hydropower generation can exceed the electricity demand for some part of the year, with spillage of water or curtailment of wind power as a consequence.[12]

Hydropower is scheduled so as to replace the most expensive generation in the system. Since hydropower is storable, a peak load increase by one unit in a hydro dominated region, e.g. northern Sweden or southern Norway, can be compensated for by increased thermal generation at some other time in any of the neighbouring regions. Marginal costs in northern Sweden and southern Norway are thus stable at levels given by marginal costs during periods of low load in neighbouring regions.

Variation management with hydropower follows the simple principle that imported power from a region with high wind or solar power penetration (e.g. western Denmark) supplies the load of some hydro dominated regions (e.g. south Norway) during hours of low load or high wind (or solar) power production. The hydropower dominated region use hydropower both to cover domestic electricity demand and for export during peak load or low wind and solar power generation.

11 Alternatively, capacity markets may be viewed as a way for incumbent utilities to protect the value of their assets rather than a way to protect electricity consumers (see Chapters 2 and 13).

12 Note that hydropower is not available in all systems. See Chapter 3 on the relative global resource availability of solar, wind, hydropower and other renewables as well as their temporal and spatial distribution.

Figure 11.5 gives modelled yearly trade flows between northern Germany and Norway by 2020 assuming a strong wind expansion in northern Germany and transmission investments both between Germany and south Norway and internally in Germany (see Chapter 9 on the role of transmission). The figure gives that under wet year conditions, Norway exports electricity to Germany except during high wind events. Under dry year conditions, in order to maximise profits Norway imports (cheap) electricity during every low load hour to be able to export (expensive) electricity during peak load.

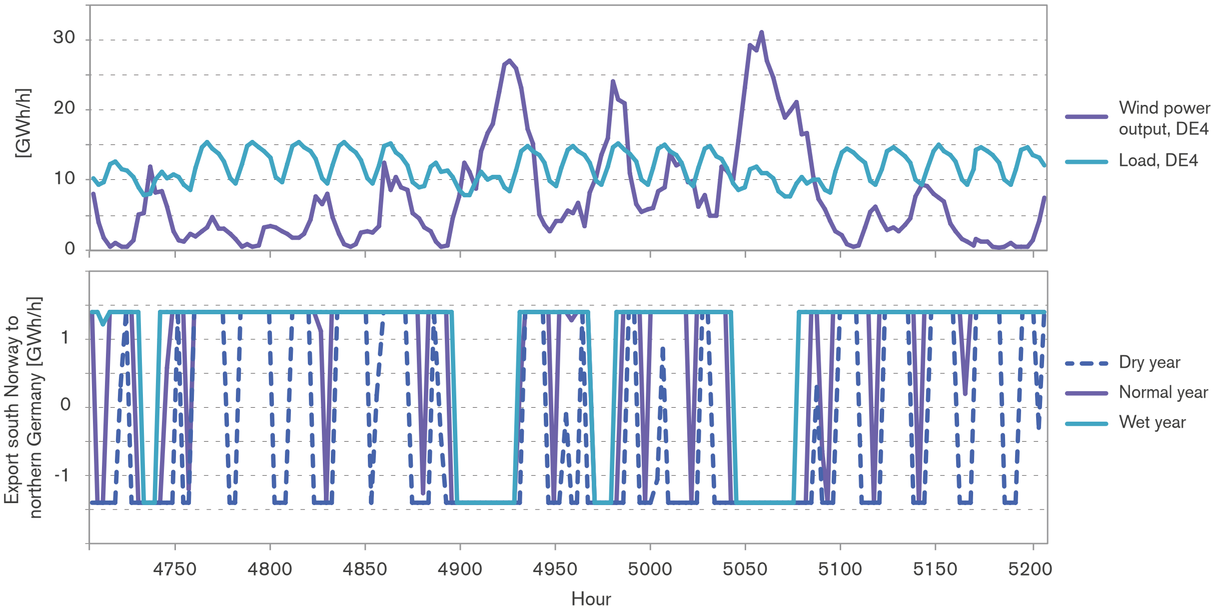

Figure 11.5 Modelled trade flows between south Norway (NO1) and northern Germany (DE4) for three weeks in spring around 2020. Source: Göransson et al. (2013).

CONCLUSIONS

Systems where wind power supply 10-20 % of the demand, cycling costs of thermal units are low. Cycling costs due to solar penetration at the same level are expected to be even lower.

Wind power generation is uncorrelated with the load and typically reduces the competitiveness of base load units whereas solar power generation is well correlated with the load and therefore typically reduces the operation hours of peak load units. Unlike thermal units, hydropower combines good cycling properties with low running costs and is therefore a good complement to intermittent renewables in general.

As the wind and solar power supply larger shares of the yearly demand for electricity, the operation hours of thermal units will decrease. However, there will still be hours of low wind and solar power generation. The need for capacity rather than energy favours thermal units with low cycling costs and low investment costs as complement to wind and solar power.