Chapter 2
Primer on Distribution Electricity Networks

This chapter gives a brief overview of the electricity distribution network. This knowledge is important to understand some of the core features of the network and the corresponding data, what are the main of applications, and how to create an appropriate forecast model.

2.1 The Electricity Distribution Network and Core Concepts

In the traditional electricity network, electricity is generated at the transmission level via conventional fossil fuel generators such as coal, and gas, and also nuclear fission. This is then supplied to consumers by first transporting the electricity over long distances at high voltage via the **transmission network**, and then stepping the voltage down and transferring more locally via the **distribution network**.

The distribution network typically starts at the so-called **grid supply point** where power is transferred from the transmission to the distribution network, and then is stepped down through various substations until it reaches the consumer. Larger consumers will be connected at higher voltages whereas residential consumers will be connected at the lowest voltage. The objective for the transmission network operator (TSO) is to match supply and demand by either increasing or decreasing the generation supplied, or the demand consumed. The focus of the traditional network is very much on the generation side.

With the transition towards a low carbon economy, the electricity networks have become much less centralised and much more diverse. There are two main developments. Firstly there has been an increase in renewable energy generation including wind, solar and even tidal. Rather than generating energy at the highest level of the transmission network renewable sources often operate at lower voltage levels and more locally to where electricity is used. For example, for rooftop solar photovoltaics, the energy generated may be directly used by the occupants of the building.

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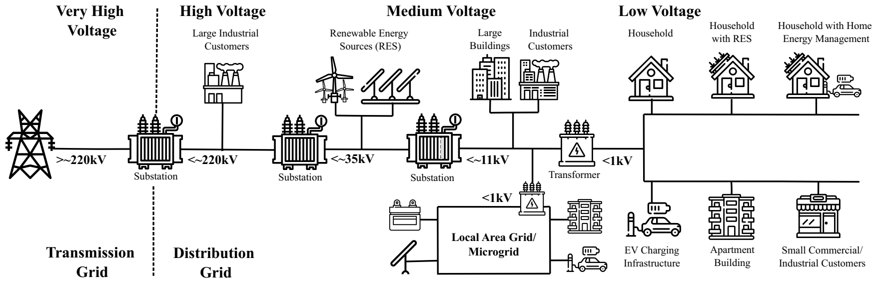

Fig. 2.1 Illustration of the electricity grid as well as the low voltage area, the focus of this book. Reprinted from [1] with permission from Elsevier

The second major development is the increase in **low carbon technologies** (LCTs) such as heat pumps and electric vehicles (EVs). These are promoted in order to decarbonise both heating and transport which has traditionally been fuelled by high carbon technologies such as gas, and petrol respectively. An illustration of a more modern electricity network is shown in Fig. 2.1.

The effect of the transition to a Net Zero energy system is to create a electricity grid which has

1. Increasing demand (due to the increased number of high demand LCTs).
2. Much more localised, weather-dependent energy generation.

These make the network much more complicated to operate and maintain security of energy supply. For one, more LCTs increase the stress on the networks which have not been designed to cope with many heat pumps or electric vehicles being connected. Secondly, the generation in a local area of a network may be much higher (or lower) than the local demand. Further to this, wind turbines do not generate energy when the wind isn't blowing, and solar panels do not generate when the sun isn't shining. This weather dependence makes renewable generation less reliable, being much more volatile and intermittent. Some ways to solve for this are to utilise storage devices (e.g. see Sect. 15.1 for an example with batteries) so that energy can be "moved" to times it is needed by storing the energy when generation is high but demand is low and then releasing the energy when generation is low and demand is high.

The lowest voltage level of the network is the step down from the **secondary substations** to the final consumers. From the secondary substation, the demand will be split into individual **feeders** (up to around six) which usually follow the roads and streets and then *feed* electricity to the individual consumers. These feeders can connect to a range of different consumers, from a single larger consumer (say a supermarket) or to about a hundred smaller consumers (usually residential), and every combination inbetween. In addition, feeders also supply electricity to other street furniture such as lighting, traffic cameras, elevators etc.

Although this book will focus on the distribution networks in general, the most challenging area is the low voltage network. This can be roughly defined as the area from the **Primary substation** (about 11 kV) down to the final household (see Fig. 2.1). This has many more unique challenges as will be described in the next section.

2.2 Low Voltage Networks

The low number and variety of connections to the low voltage (LV) network means there are two main challenges which are intensified compared to the higher voltage or national levels of the network.

The first problem is that demand is relatively volatile. Since on the lowest level of the network there is only on average around 40 or 50 consumers (but can be as few as a single larger consumer), the demand is much spikier and less regular than the aggregation of 100s or 1000s of consumers as is true at the next step up in the distribution network. Thus it is much more difficult to predict or model the demand. This makes things complicated for **distribution network operators** (DNOs) who are in charge of the cables and are required to maintain a supply of electricity to consumers. It is much harder to optimally plan and manage the network when the demand is less predictable with varying degrees of uncertainty. Further to this the demand is likely to change much more as increasing numbers of households and businesses install EV charging, PV solar and heat pumps.

The second problem is that low voltage networks are much more sensitive to individual demands. For example, a few LCTs (say heat pumps) will have a much bigger relative impact on the LV network than at the higher voltage levels. It only takes a few large devices to completely change the demand patterns. Many current networks have been designed without LCTs in mind which means they do not have the head room necessary to allow excessive numbers of high demand appliances or renewable generation sources. For the LV network to operate properly and protect against damage, the network should operate within particular constraints. The cables are built to be able to take a certain size of demand, and if this is exceeded it can break the network and cause outages. There are several ways that the network can be broken and we briefly discuss them below.

The first is **thermal constraints**. Usually the demand can exceed the specified headroom for a short period (an hour or two) but if the demand is higher than the thermal capacity of the cables for too long then overheating will occur and the network may be damaged. The demand should be lowered by either reducing the demand, e.g. through demand side response, or by utilising battery storage devices. The chance of exceeding the thermal constraints has been increasing due to the increase in low carbon technologies like electric vehicles which often have high power ratings (7 kW even for the slower chargers) and will also be utilised at similar times (when people come home from work they may all plug in their EVs).

The second potential problem is **voltage constraints**. The voltage must operate within particular limits. In the UK, the last mile of the network is a nominal 230 V and should be no less than 216.2 V (i.e. −10%) and no more than 253.0 (+6%). This can be different depending on the country of course. Voltage decreases when there is more demand on the network, and increases if there is generation on the network. As power flows down a cable to consumers and more demand is applied the voltage drops. If the demand is too high, then the voltage may drop outside the lower constraint. If there is excess generation on the network (from solar photovoltaic generation from numerous consumers) then the voltage may increase beyond the upper constraint. In both cases this can cause network failure and damage to electrical components.

The final main problem is **phase imbalance**. The electricity in a feeder is often split into three **phases** through individual wires and the current and voltage are 120 degrees out of phase with each other. The details here are not required for this book, but the importance is that demand should be roughly equal across the three phases. If not then this can generate power losses, reduce the lifetime of appliances, and increase the heat within the cables, causing damage and possible failures. Connections to a feeder in the last mile of the LV network will split across consumers but it is unlikely to be evenly distributed. One phase may have many more consumers than another, hence LV networks are likely to be particularly unbalanced. The uptake of EVs and heat pumps will likely lead to further imbalances.

2.3 Some Features of Distribution Networks

Compared to system or national level demand, there is much less known about low voltage demand since it has not been monitored or analysed as extensively. One example, which will be demonstrated in the case study in Chap. 14, is the effect of temperature. This is generally considered a strong driver of national demand in the UK because a lower temperatures should mean more electrical heating appliances and hence greater demand. In hotter countries with air conditioning there may also be an increased demand when the temperature is higher. However, this may not necessarily be the case at the low voltage. Much of the heating in the UK at the time of writing (although this should change as the country moves towards lower carbon alternatives) is fuelled by gas. Thus if a network has only a few consumers which use electricity, there may be a small, or zero relationships with the temperature values. In any case, weather is a potential driver of demand on an LV network, and should be considered as a potential input for any forecast model.

Since electricity networks are radial it means that they are arranged in trees. Electricity is stepped down from higher voltages down to lower voltages and therefore energy typically flows in one direction. This suggests the following question: Is the demand at a substation simply an aggregation of the connected loads down stream? The answer is no, and for the following main reasons:

1. **Losses**: There are losses of energy as it travels through the cables. In other words, not all electricity makes it to its final destination. The total energy of all loads on a substation will therefore be lower than the energy recorded at the substation

itself which needs to supply more energy to account for that which is lost. These are typically small, around 5% in some instances.

2. **Switching**: Often electricity has to be rerouted to entirely different nearby networks. This could, for example, be because there was a shortage in the other network and therefore another substation has to temporarily supply the electricity (through some linking box).
3. **Unknown connections/demands**: In practice it is unlikely that all the downstream connections on a substation are known, and even when the roll-out of smart meters is complete, it is unlikely that all households will have half hourly electricity readings.[1] So in many cases the substation load cannot be fully estimated using the known downstream loads.

To add to the above complications, it cannot be assumed that the substation electricity flows in only one direction. With the increasing numbers of distributed generation, electricity flows are now reversing direction in some networks, something they were not originally designed to do. These complications must be taken into account when developing forecasts at low voltage level. If the effect of each of the above is significant then they must be integrated into the modelling. Switching is one of the more difficult to deal with as it requires taking into account a temporary shift in the demand behaviour which will then shift back at a later date. For this reason adaptive methods which quickly learn the new demand behaviour may be preferable and regime switching models may also be useful (Sect. 13.6.3). To deal with the misalignment in load between the substation and aggregated downstream loads (either through unknown connections or losses) the difference itself could also be included in the modelling, since this will either be a scaling (losses) and/or be itself an aggregate of the few unmonitored consumers.

So what does distribution, or even individual consumer load look like? For simplicity, complications such as losses and street furniture (they will be relatively small) are ignored, and it is assumed there is no switching behaviour. Examples of residential demand are shown in Fig. 2.2. These are very diverse and no two are the same, although there are some similar features. For example, since occupants are often at work during the day and more active in the morning and evening, the corresponding demand usually has peaks at similar times. Further, most households have weekly and daily seasonality, with Saturdays and Sundays having different patterns than typical weekdays. This is not obviously true for households which may be occupied by shift workers etc. There are also some technologies which produce particularly strong demand features, such as electric vehicles and overnight storage heaters which can create large overnight demand.

The difference in household demand is worth highlighting further. Even when the homes are very similar (e.g. 1920s Semi-detached), and the occupants have similar socio-demographics, their residential demand may be very heterogeneous, with different regularities and distributions of daily demand. Figure 2.3 shows the half-hourly demand of four randomly selected households on a Monday. The top

[1] For example, some households will not have a suitable location for installing a smart meter, or there may not be sufficiently available signal to transmit the information.

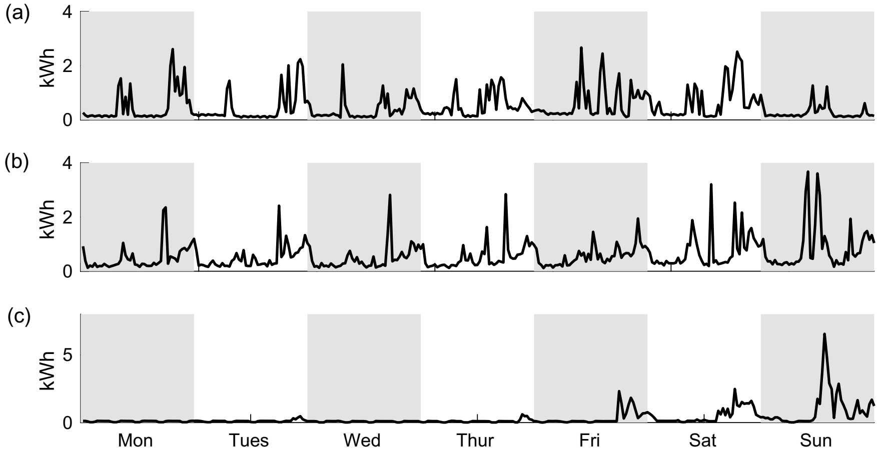

Fig. 2.2 Three examples of residential smart meter demand over a week at half hourly resolution. Constructed using data from the CER Smart Metering Project—Electricity Customer Behaviour Trial, 2009–2010 [2]

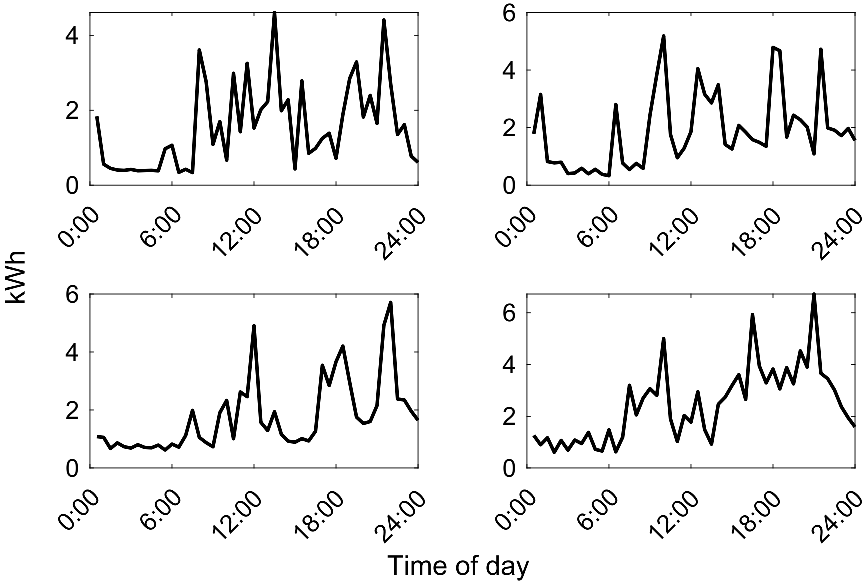

Fig. 2.3 Examples of half hourly demand profiles over a single Monday for aggregations of five households. Constructed using data from the CER Smart Metering Project—Electricity Customer Behaviour Trial, 2009–2010 [2]

two in this case have higher demands around midnight than the bottom two, whereas the bottom two have much more distinct morning and evening peaks. This suggests the bottom two have more regular "9 to 5" jobs outside the home, with peaks in the morning due to switching on say kettles or electric showers, and then evening peaks due to returning home, and perhaps cooking or switching on the TV etc. In contrast, the top two profiles seem to suggest a least some of the occupants within the house most hours of the day as there is peaks throughout the day. This could be from someone performing their job from home, or could be other household chores etc. Identifying what appliances may be in operation by analysing the household profile is another entirely separate branch of energy analytics (outside of the scope of this book!) called **Non-Intrusive Load Monitoring** or NILM.

Small to medium enterprises (SMEs), such as hairdressers, churches, schools, shops etc. are also very different even within the same categories (pubs for example) although they will be more similar than across categories. The demand magnitude and its distribution is often based on the operational hours and the type of appliances that are used within the SME. For example, offices will be determined by computing equipment, heating and lighting, usually during the day. In contrast a pub will be based on heating and lighting, but also hand dryers, pumps, cooking appliances, and refrigeration. The demand will also be mainly within the evening. Some real profiles of SME demand are shown in Fig. 2.4. The clear daily regularity of the first two SMEs is very apparent as is the fact that they are both closed on Sunday (in fact the first SME is also closed on Saturday). The other consumer has much more volatile behaviour and there is some demand on all days of the week.

Since distribution network demand is mostly made up of the aggregation of different residential and commercial consumers their demand distribution will be as diverse as the possible combinations of consumers. However, distribution, and especially

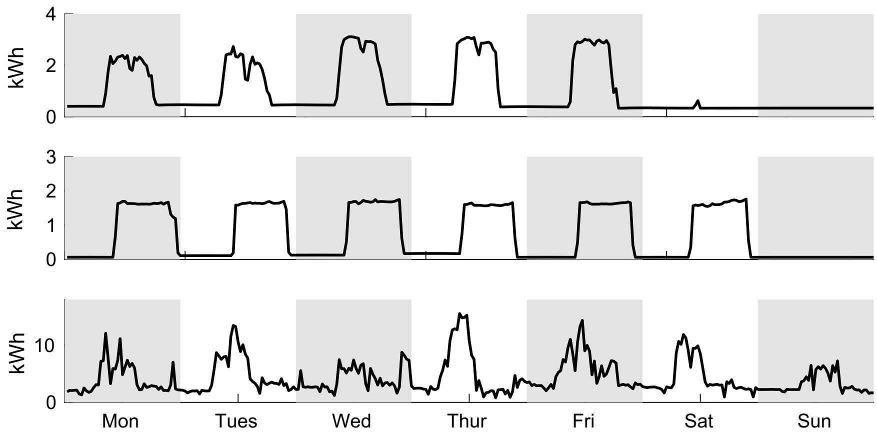

Fig. 2.4 Three examples of smart meter demand for SMEs over a week at half hourly resolution. Constructed using data from the CER Smart Metering Project—Electricity Customer Behaviour Trial, 2009–2010 [2]

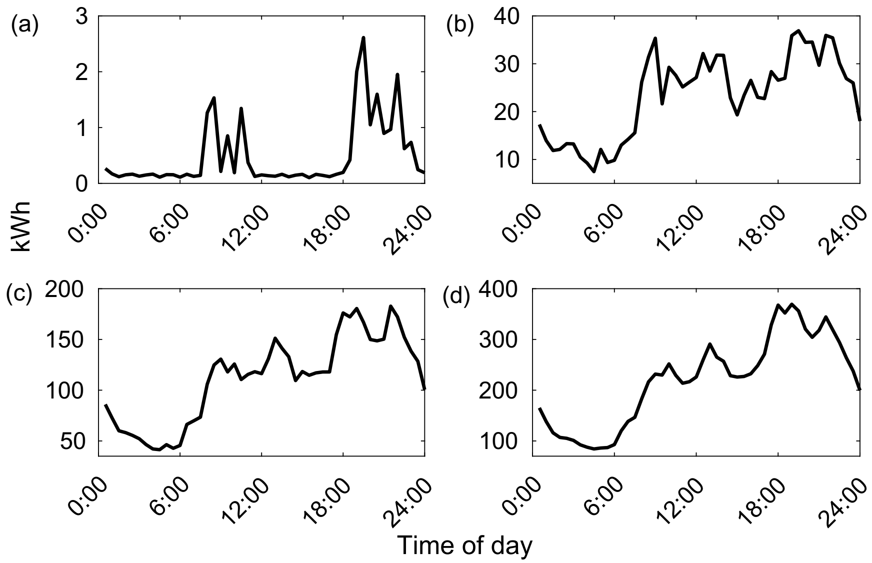

Fig. 2.5 Examples of half hourly demand profiles over a single Monday for **a** a single household, **b** the aggregation of 50 households, **c** the aggregation of 250 households, and **d** the aggregation of 500 households. Constructed using data from the CER Smart Metering Project—Electricity Customer Behaviour Trial, 2009–2010 [2]

LV, networks are very diverse in terms of the numbers and mixture of consumers. Figure 2.5 shows the aggregation of different numbers of individual (residential) smart meters for a single Monday (Another example for a full week is shown in Sect. 1.2, Fig. 1.2). LV feeders with larger numbers of consumers (all residential in this case) have much less relative volatility and are more regular. Further to this, it must be remembered that real LV feeders are not connected to purely residential consumers, but also supply energy to different street furniture and can also include commercial consumers. A single commercial consumer can change the dynamics of a network significantly since they often have larger demand and they may use energy at very different times: e.g. a hairdresser will have higher demand during the day, but households typically have evening peaks. The data analysis for the case study in Sect. 14.2.2 includes some examples of real feeders (Fig. 14.1) and shows that even when they have similar numbers of residential connections they can produce very different demand over the year and on special days such as Christmas. If the feeders are purely residential then their demand profiles look like smoothed versions of individual residential demands (see Fig. 2.5). The effect of a single commercial connection is demonstrated in Sect. 14.2.2, Fig. 14.3.

2.4 Managing the Distribution Network

So what tools and solutions are required for the distribution networks to ensure they work properly and consumers can be supplied with the energy they need?

As discussed in Sect. 2.2 some of the major issues to be managed are phase imbalances, voltage constraint violations and thermal constraint violations. These were relatively well managed in the last few decades and the worse case scenario usually required digging up the road to install larger cables to handle the increased demand. With increased uptake of LCTs and more distributed renewables, new solutions may be required since the traditional network reinforcement upgrades will be quite expensive and disruptive.

Instead, what is envisioned is the move towards a **distribution system operator** (DSO) who will control the supply and demand on the distribution network much like the electricity system operator matches the supply and demand at the national level. The DSO would do this by procuring various flexibility services from across the network, for example this could be demand management where demand is controlled via a storage device (Sect. 15.1), or consumers can be required to change the demand of particular appliances by responding to signals from system operators via so-called *demand side response* (Sect. 15.2).

There are also ways to persuade consumers to change demand by offering new incentives such as smarter tariffs to consumers. Instead of the current practice of a simple flat unit-rate for use of electricity, the charges can change over the day to identify periods of high or low use, or can be dynamic to respond to the current conditions of the network. They can also be tied to renewable generation to try and utilise cleaner energy.

With these consumer focused initiatives, local communities may also be more involved in the managing of the network. The aggregation of hundreds or thousands of controllable assets such as EVs, heat pumps and battery devices can produce significant aggregated effects on the network and save consumers money. For example, EV charging could be co-ordinated to ensure there isn't a large charging peak when all consumers plug in their devices. Alternatively, the collective battery power of hundreds of EVs could be used to reduce network peaks and utilise more local solar PV generation. This integration of thousands to millions of controllable devices with the ability for two-way communication is often referred to as the **smart grid** and could lead to a much more decentralised energy system where power is generated and utilised locally via the smart control of the assets.

There are also emerging energy markets which are offering participants ways to make savings through their own devices to offer additional capacity, balancing services, or other ancillary services, such as frequency control. The interesting aspect of many of these applications is that for them to optimally operate their behaviours must be accurately anticipated. This book therefore, and many of the models presented, can be used to help, and indeed are necessary, to support the future energy network. A selection of applications will be presented in Chap. 15.

2.5 Questions

1. Think about your electricity usage throughout the day. What would your usage profile look like? How would it change on a weekend versus the weekday?
2. Which of your electricity usage behaviours are the most flexible? I.e. which ones could be easily moved to a different time of day? Which ones could move the most? Which ones would it be difficult to move?
3. Download a set of smart meter datasets (some are listed in Appendix D.4). Plot (using any of your favourite plotting software) a few weekly profiles from some households. Try and think about what appliances may contribute to the major demands you see. Plot the demand over a year. What is the shape? Is there any annual seasonalities or does it stay consistent over the year? What is the largest demands you see? Can you guess what they may be? Is there any unusual or anomalous values you see? Very large ones, or periods of missing data?
4. If you have an EV what would the typical charging profile look like? If you don't have an EV think about where you would charge it, would it be at home or at the workplace? Think about what some other typical charging profiles would look like. Do they have a lot of diverse load or are they going to generate a large peak from charging at the same time?
5. Reflecting on how you use heating within your home. What would the energy profile look like over a period in winter? What about the average daily demand over a year?

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