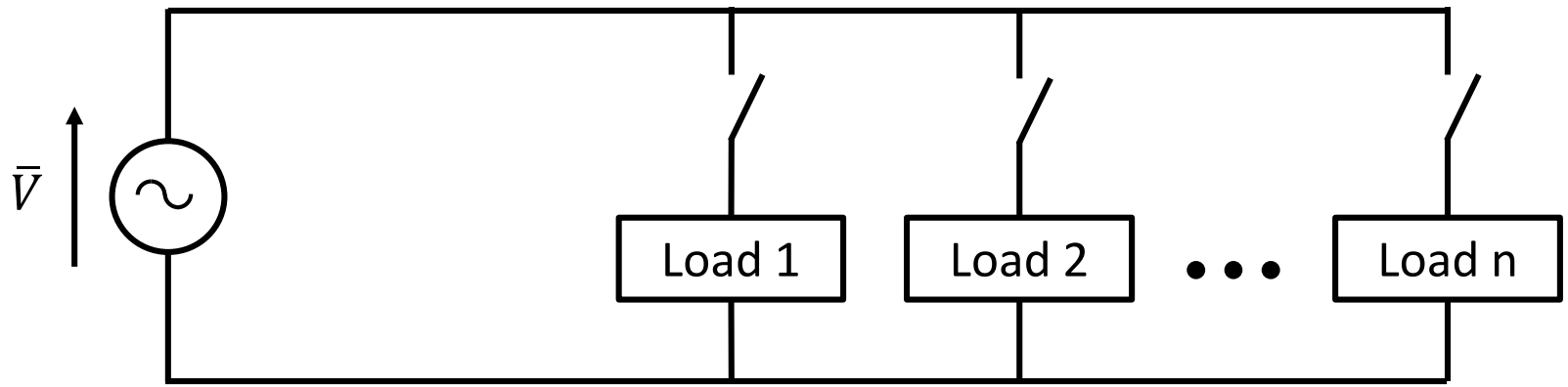
Simplified wiring diagram of a house



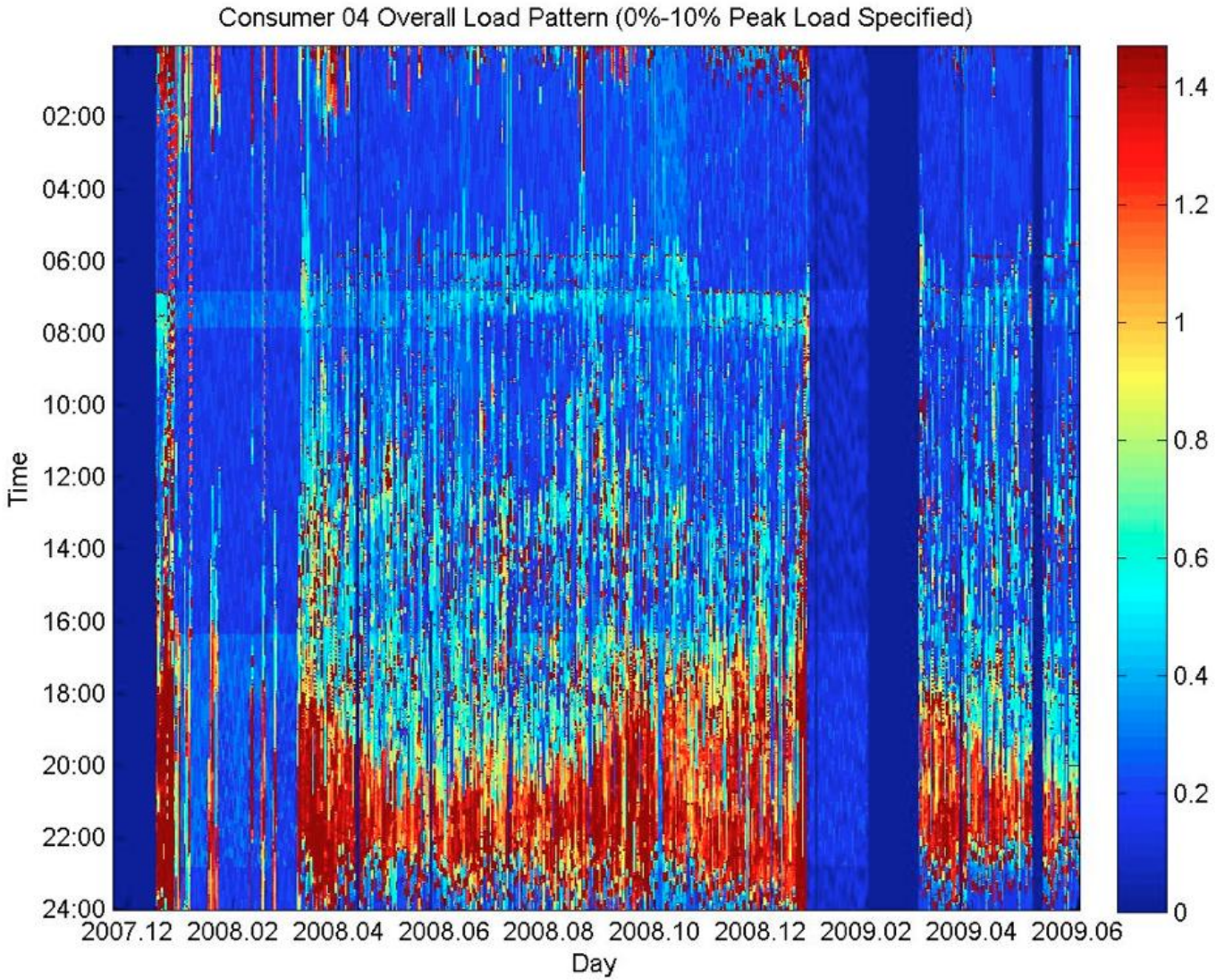
- Loads are connected in parallel
  - Within the house
  - Across the power system
- If the supply voltage remains relatively constant, we can add up the loads to estimate the total load.

Quantifying loads

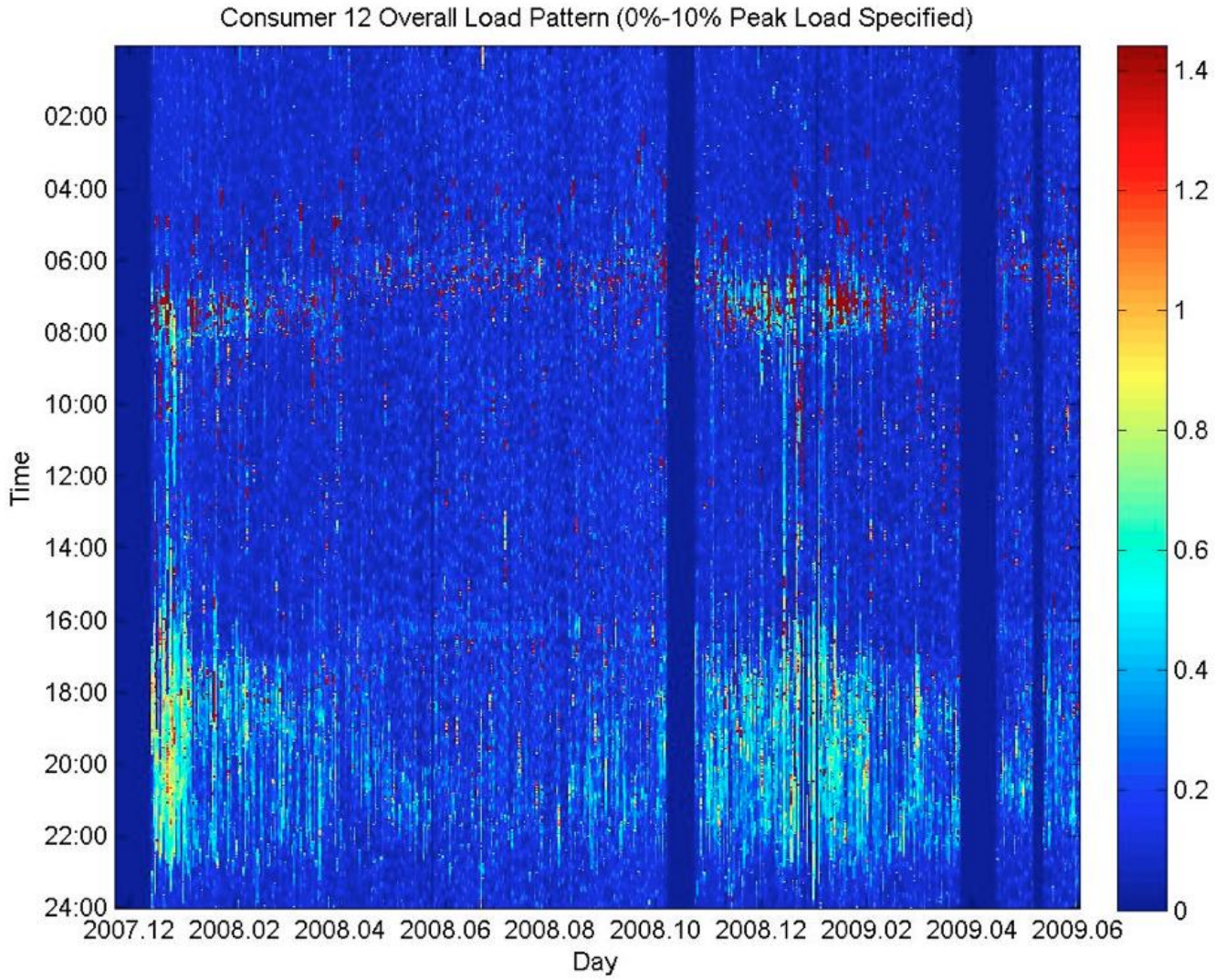
Loads are quantified in terms of power, not impedances

Appliance	Typical Rating
LED lightbulb	9-15 W
Incandescent lightbulb	60-100 W
Laptop computer	65 – 100 W
Desktop computer	250 – 500 W
Refrigerator	300 – 1100 W
Single room air conditioner	600 – 1500 W
Space heater	750 – 1500 W
Water heater with tank	2000 – 6000 W
Whole house air conditioner	2500 - 4000 W
Electric shower	8000 – 10000 W
Tankless water heater	13000 – 36000 W

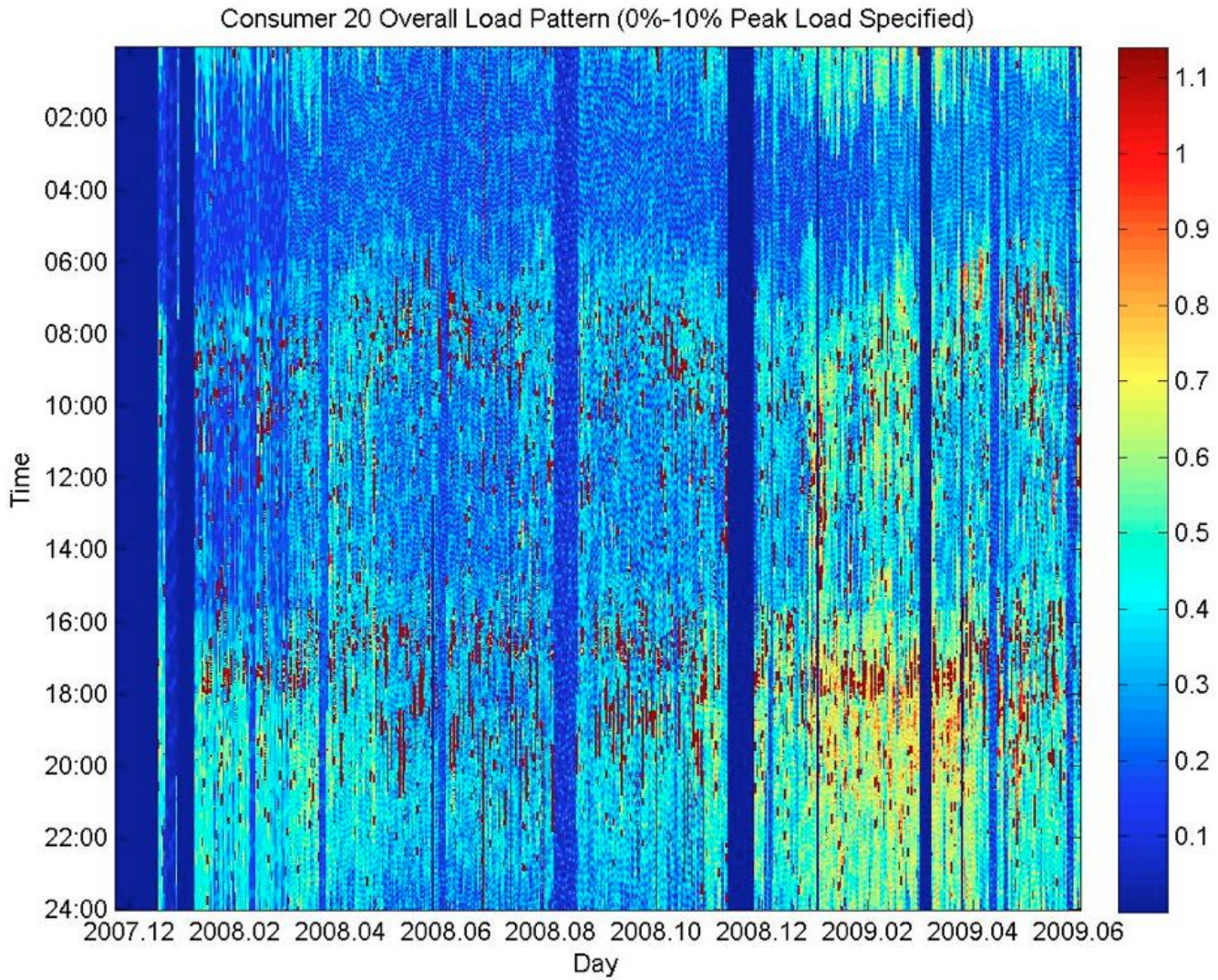
Typical load profiles of residential consumers



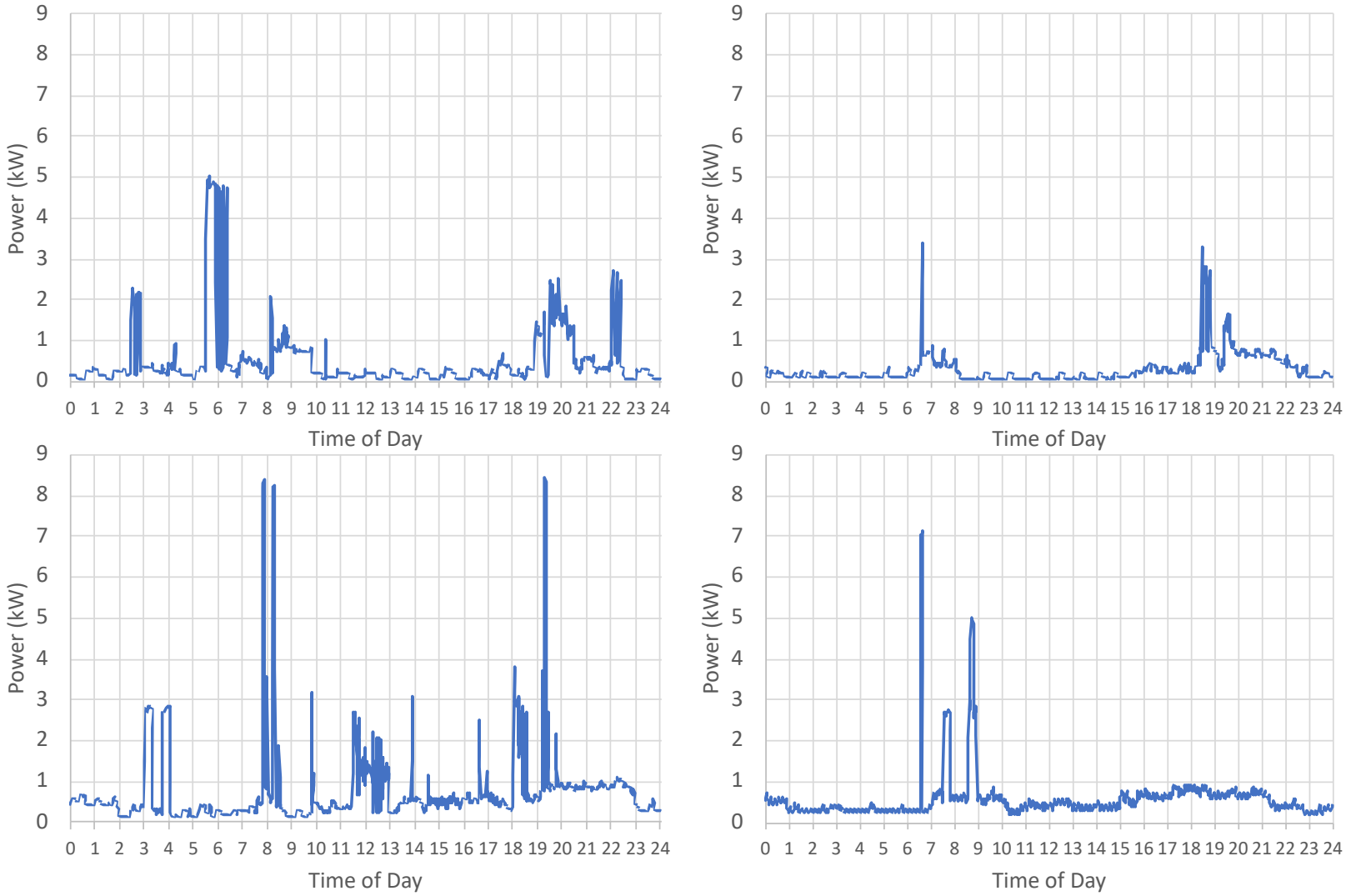
Typical load profiles of residential consumers



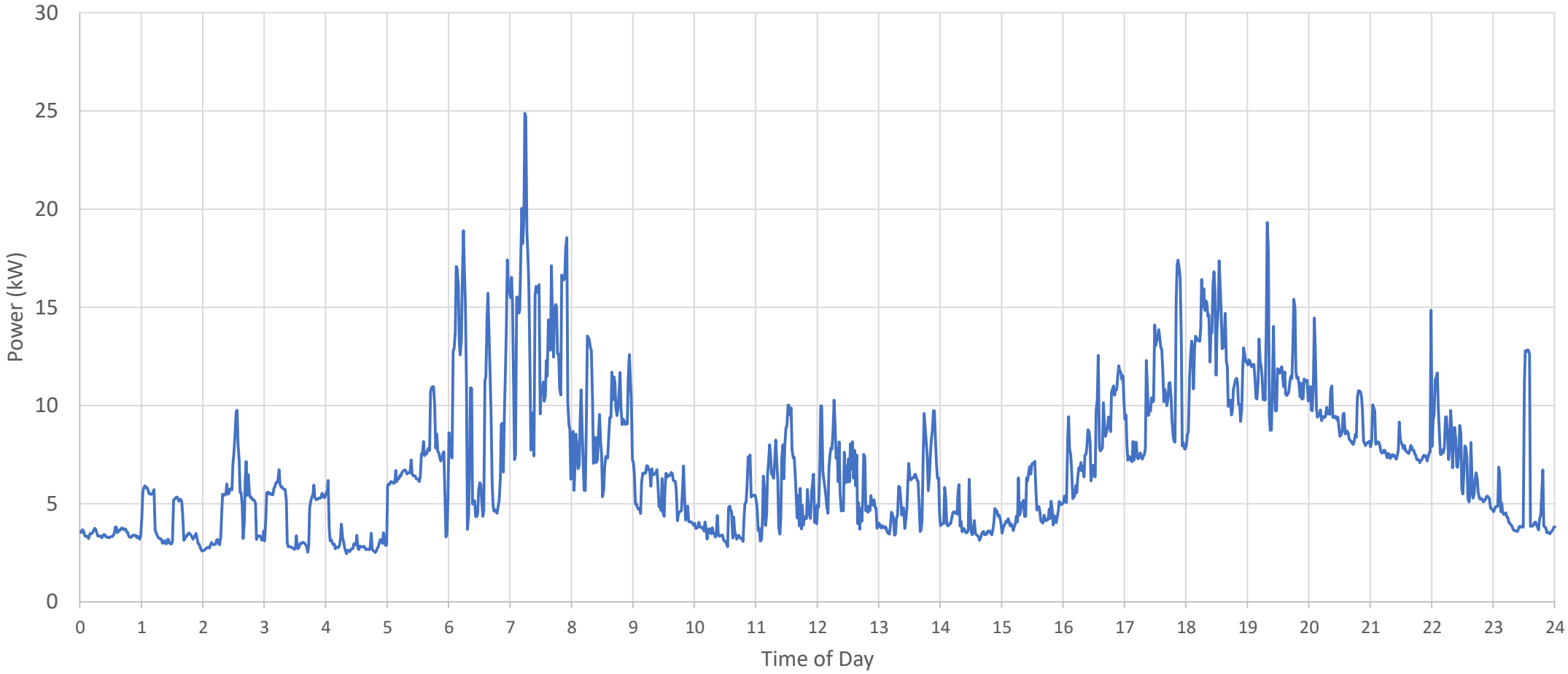
Typical load profiles of residential consumers



Power consumption profiles of fours houses, recorded every minute over the course of the same day



Aggregated power consumption profile of 16 houses, recorded every minute over the course of the same day



Summary data about the profiles of the four houses and the aggregation of the 16 houses

House	A	B	C	D	16 houses
Peak load (kW)	5.013	3.413	8.464	7.157	24.887
Minimum load (kW)	0.045	0.083	0.141	0.179	2.454
Average load (kW)	0.507	0.3027	0.7398	0.5747	6.985
Energy (kWh)	12.171	7.264	17.754	13.794	167.633
Peak/average ratio	9.88	11.27	11.44	12.45	3.56
Capacity Factor	10.1%	8.9%	8.7%	8.0%	28.1%

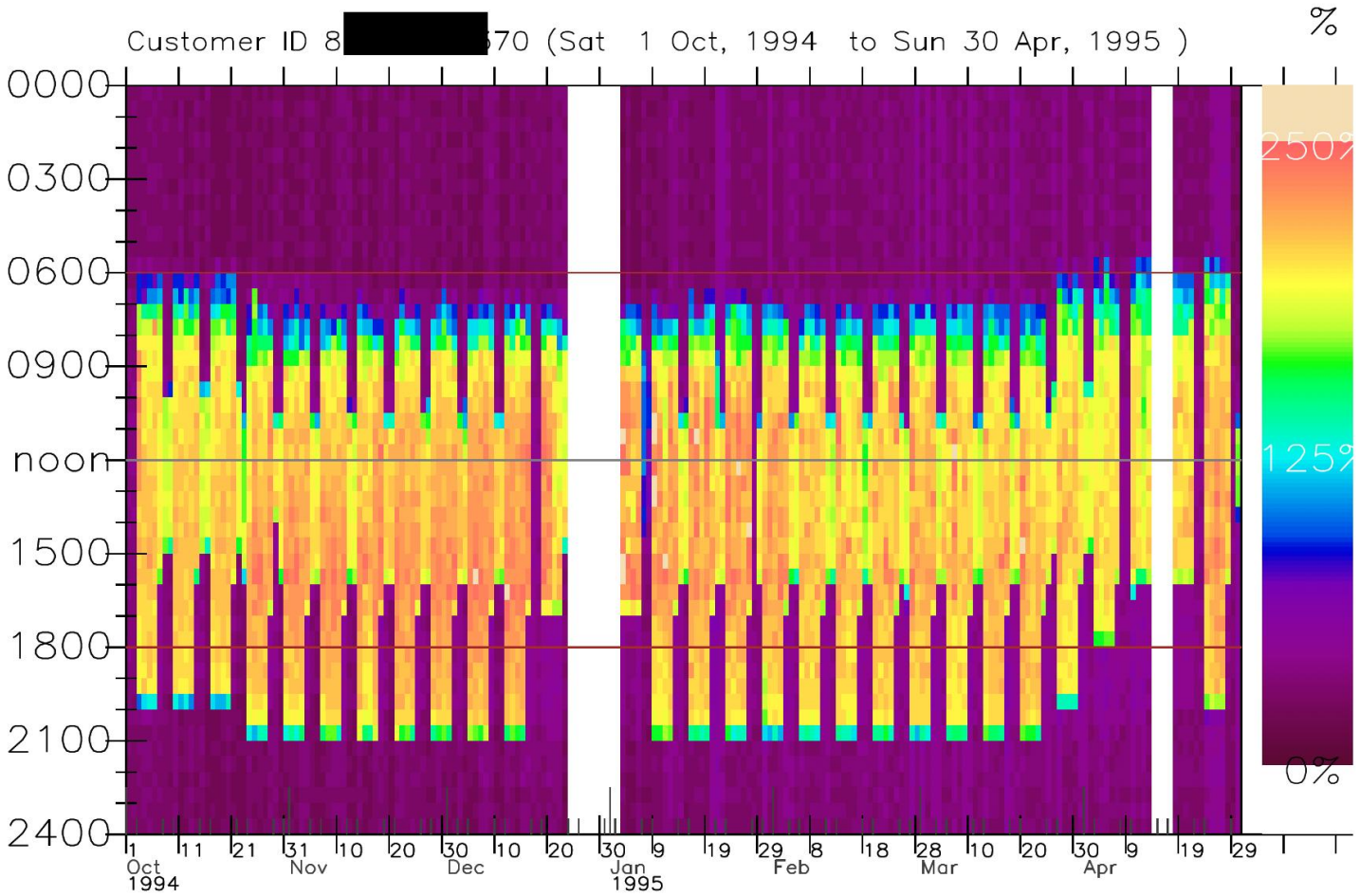
Aggregation

- Suppose that each house installs its own generation
- Must have sufficient capacity to meet its own peak load
- 16 houses separately → Need a total of 95 kW of generation capacity
- Aggregation of 16 houses → Need only about 25 kW of generation capacity

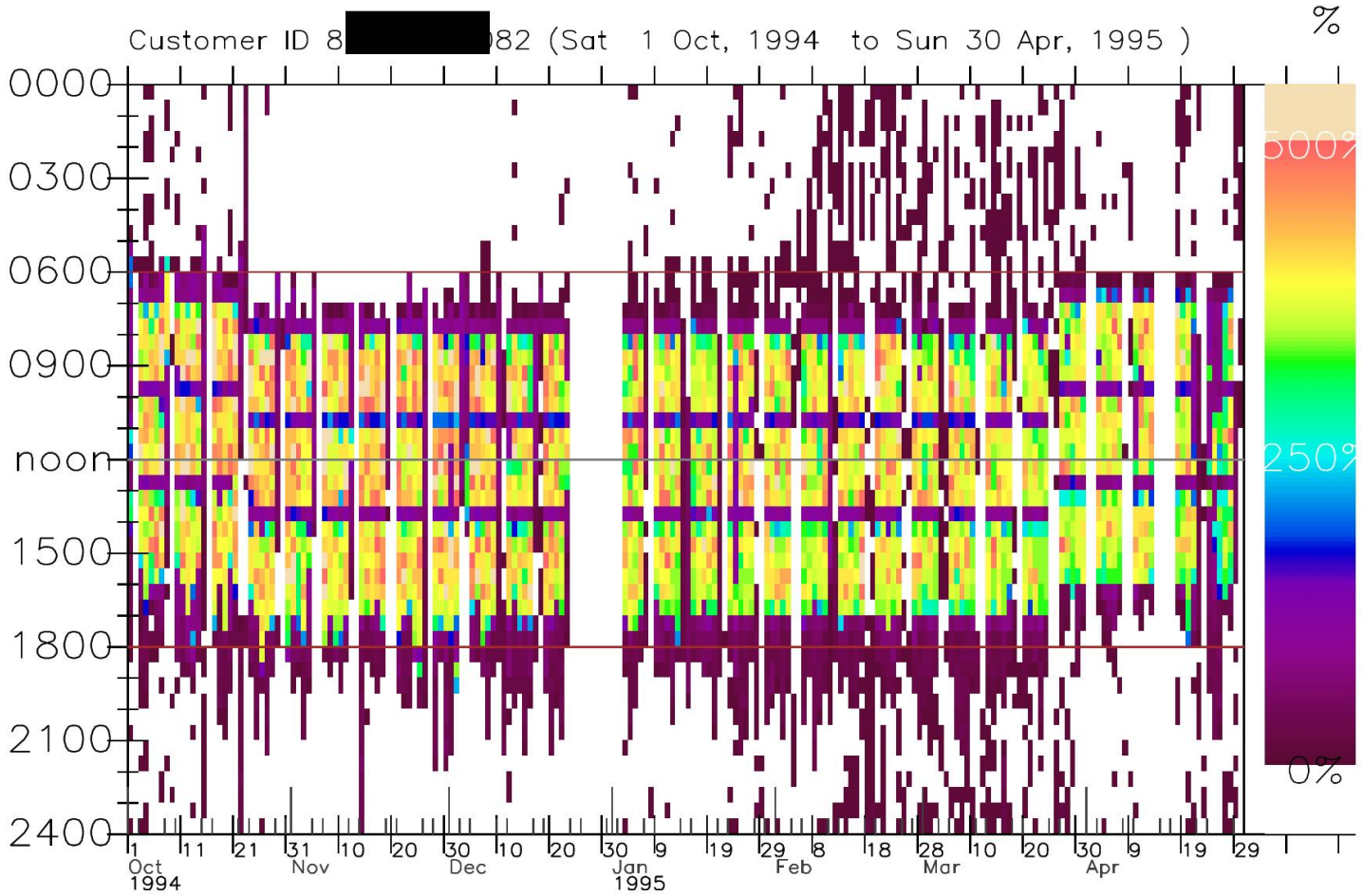
- Capacity factor: $C_f = \frac{\int_0^T P(t)dt}{T \times P^{max}}$

- Aggregation allows us to take advantage of the diversity in the demand of various consumers
- Benefits of aggregation increase as we include more consumers and more consumer types

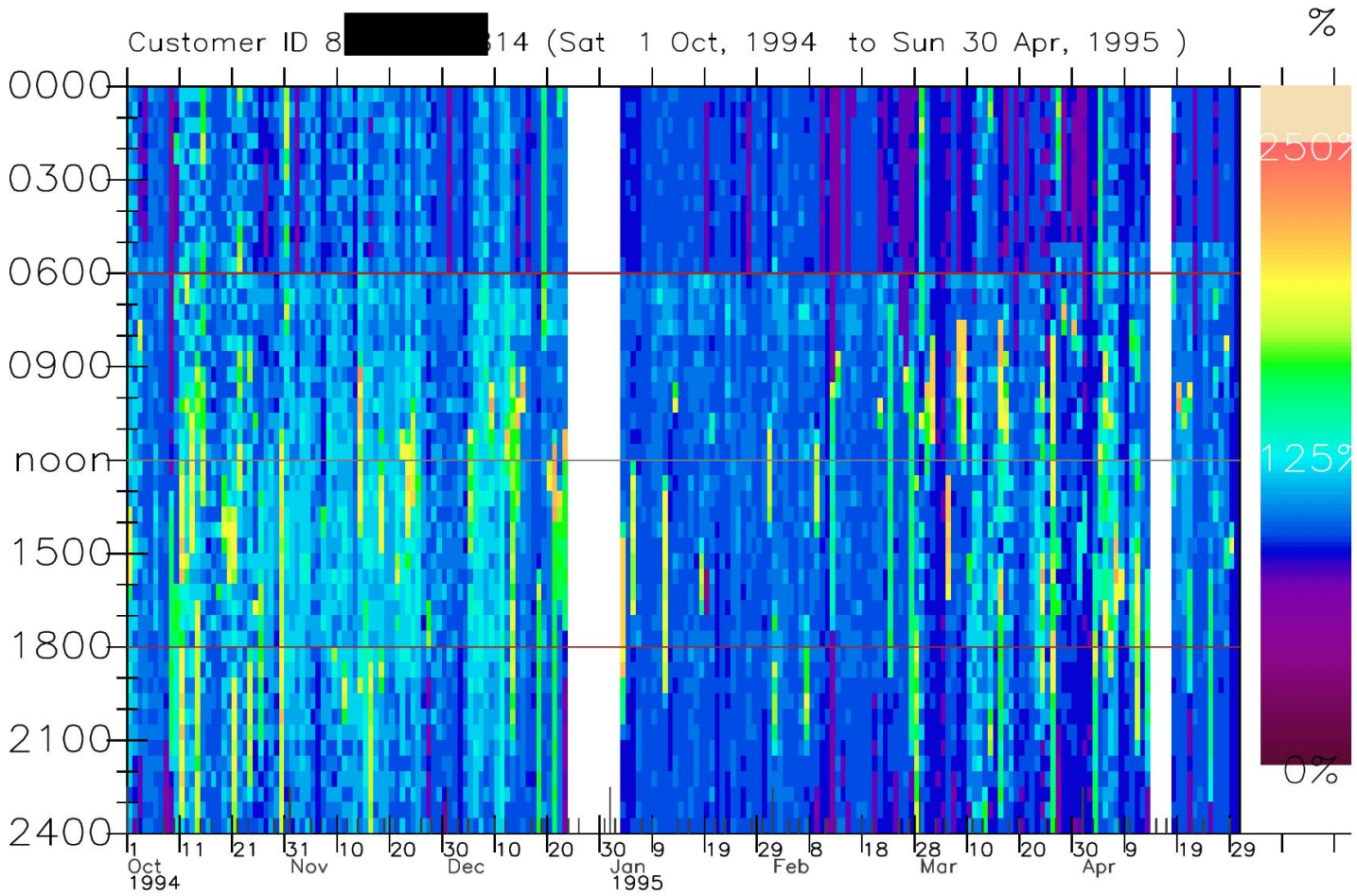
Commercial consumer: “Education”



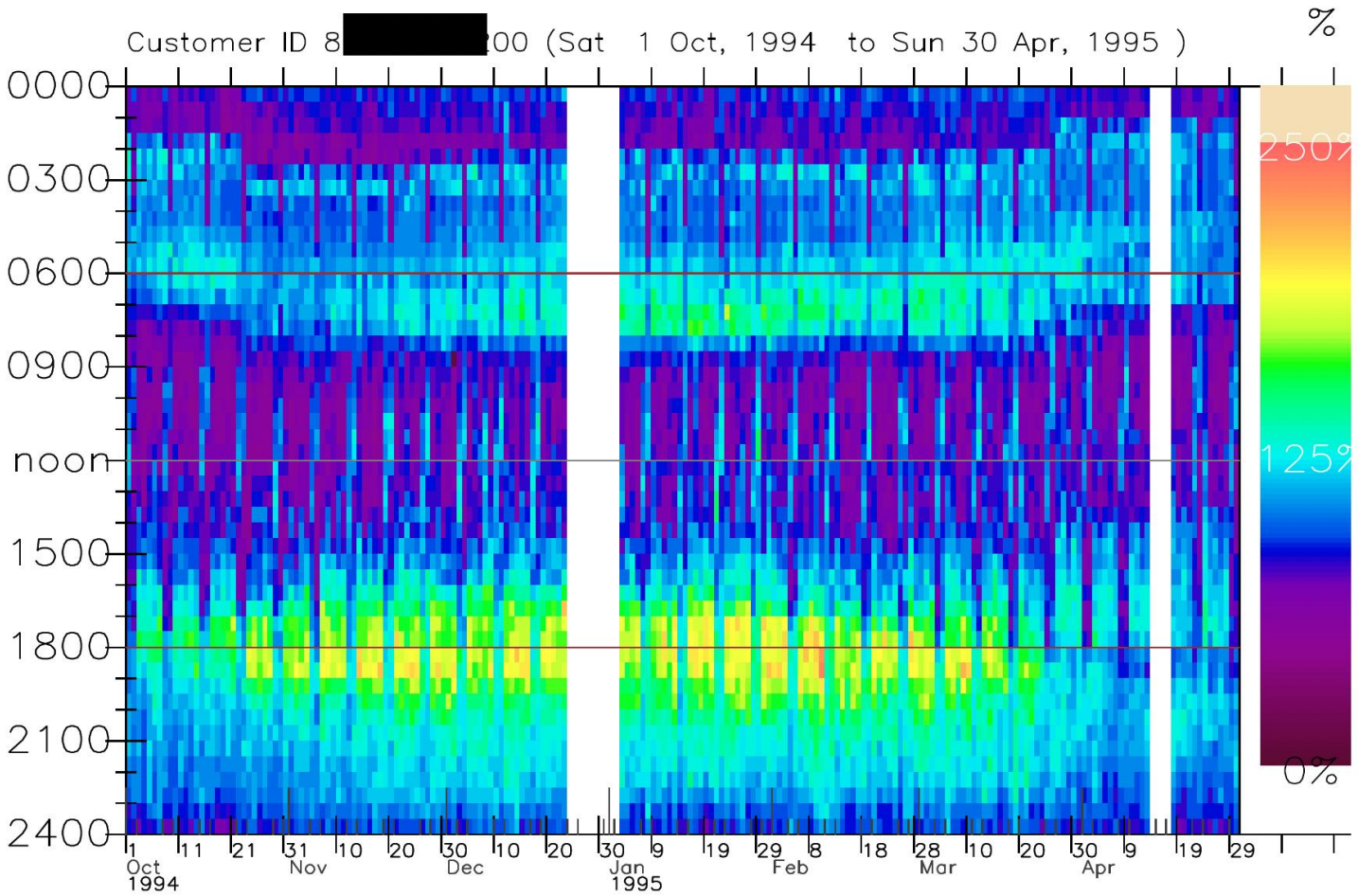
Commercial consumer: “Retail”



Commercial consumer: “Legal and Marketing”



Commercial consumer: “Hotel Restaurant”

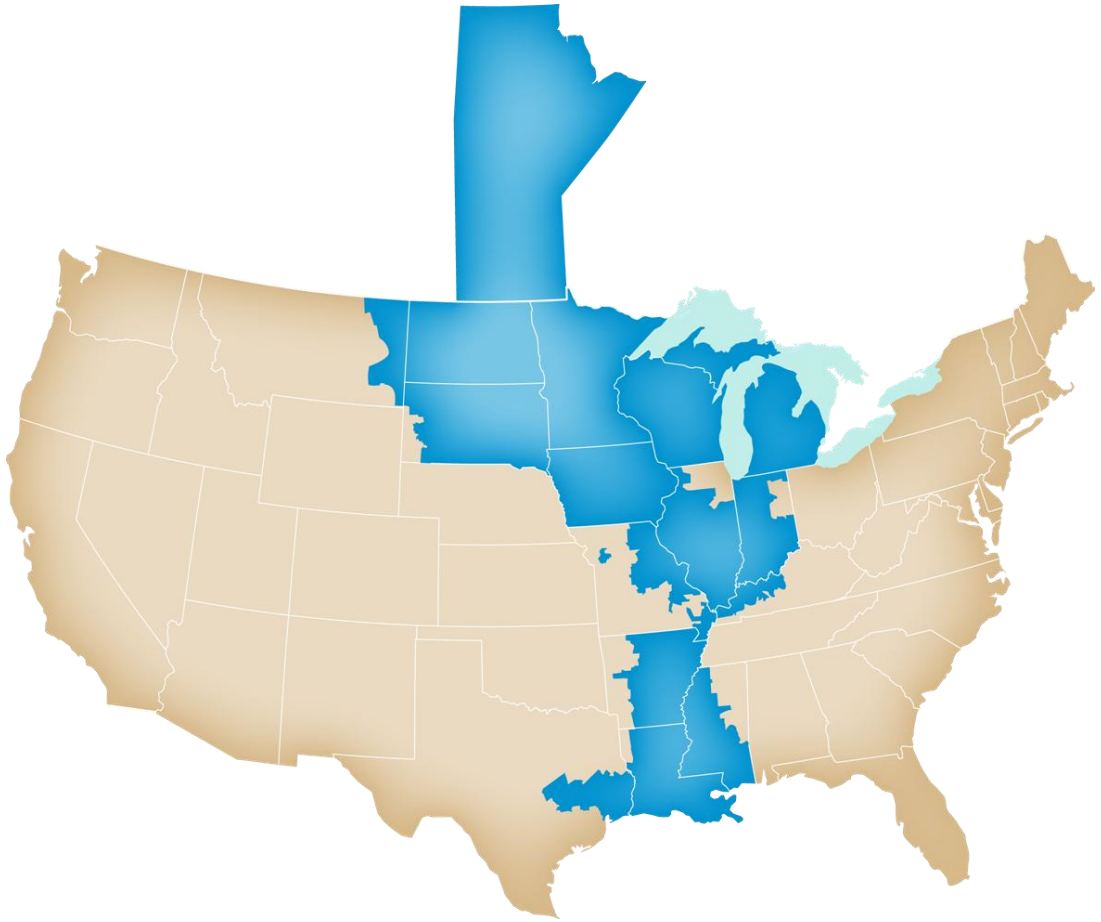


Industrial Consumers

- Wide variety of load profiles
- Depends on the type of industry
  - Process industries: (glass, aluminium, …)
    - Fairly flat load because activity is constant
  - Manufacturing industries:
    - Depends on number of work shifts

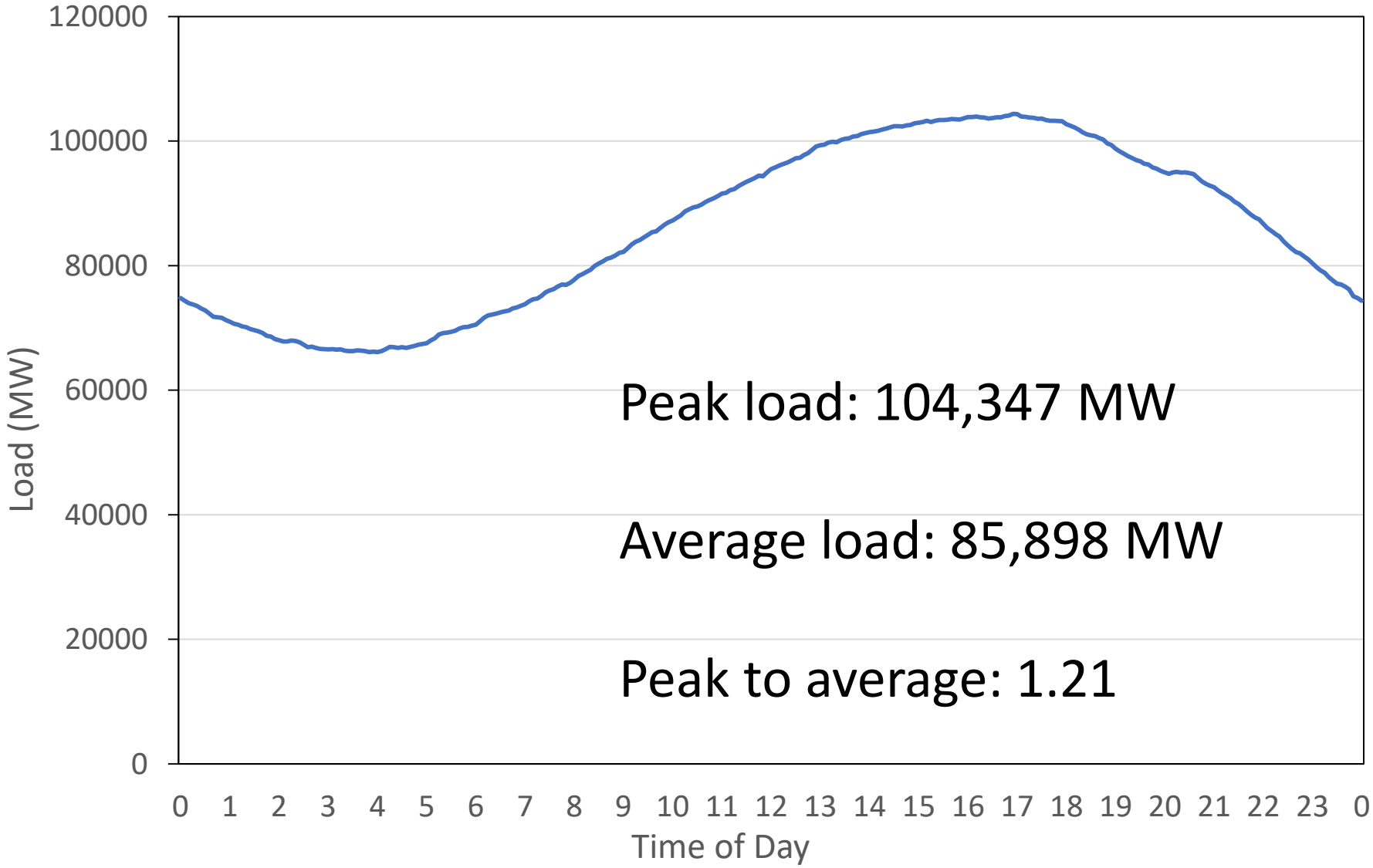
Aggregation over a large region

- Example: MISO
- 42 million consumers



Aggregated load profile for the MISO region

Data recorded every 5 minutes on August 12, 2020



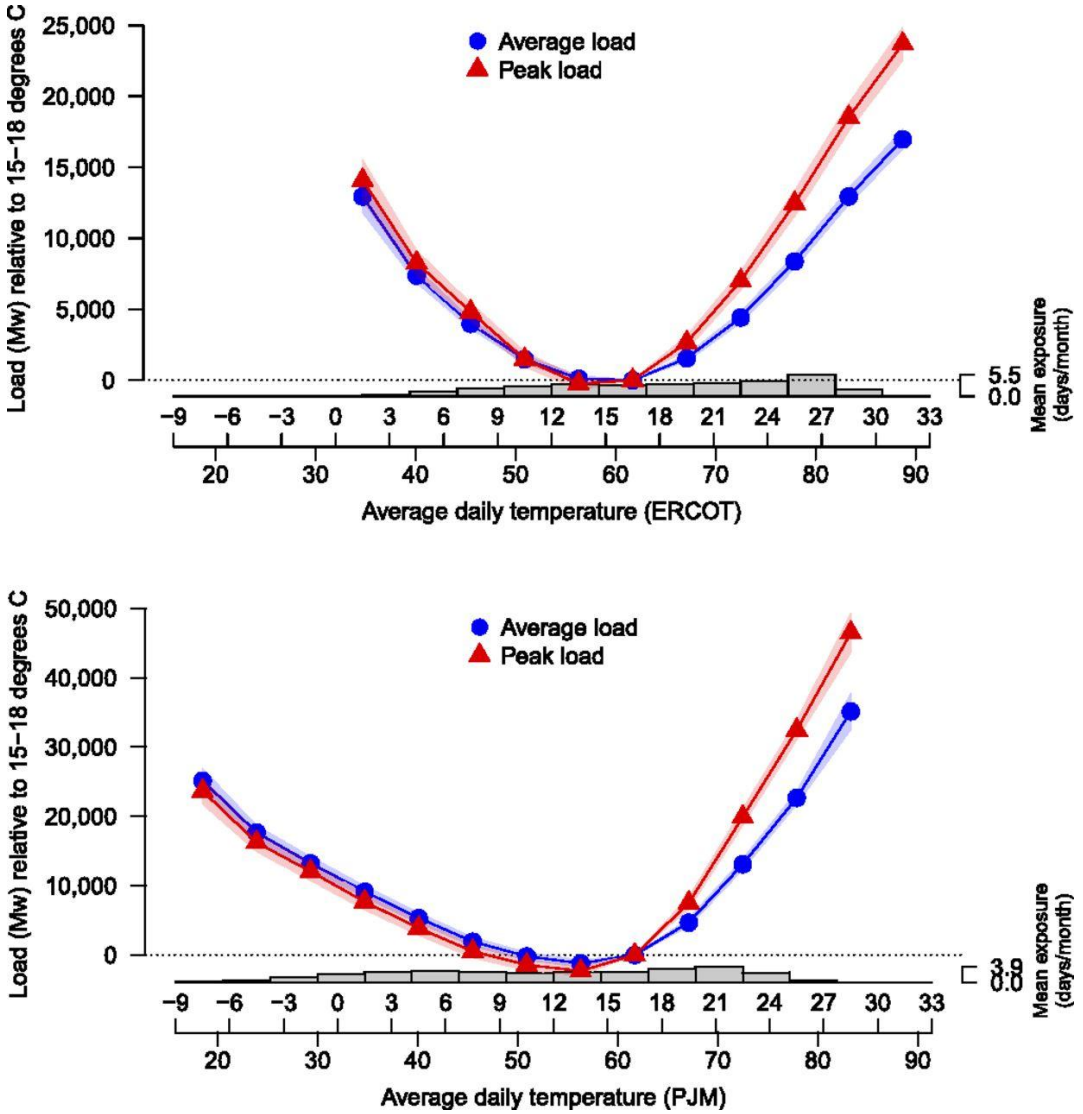
Short-term effects on load profile

- Astronomical factors
  - Time of day
  - Day of the week
  - Time of the year
    - sunrise, sunset, daylight saving time
  - Holidays
- Weather
  - Temperature, cloud cover, wind, humidity
- Special events
    - Examples: television specials, other events
    - Loss of load diversity

Effect of temperature on electricity demand

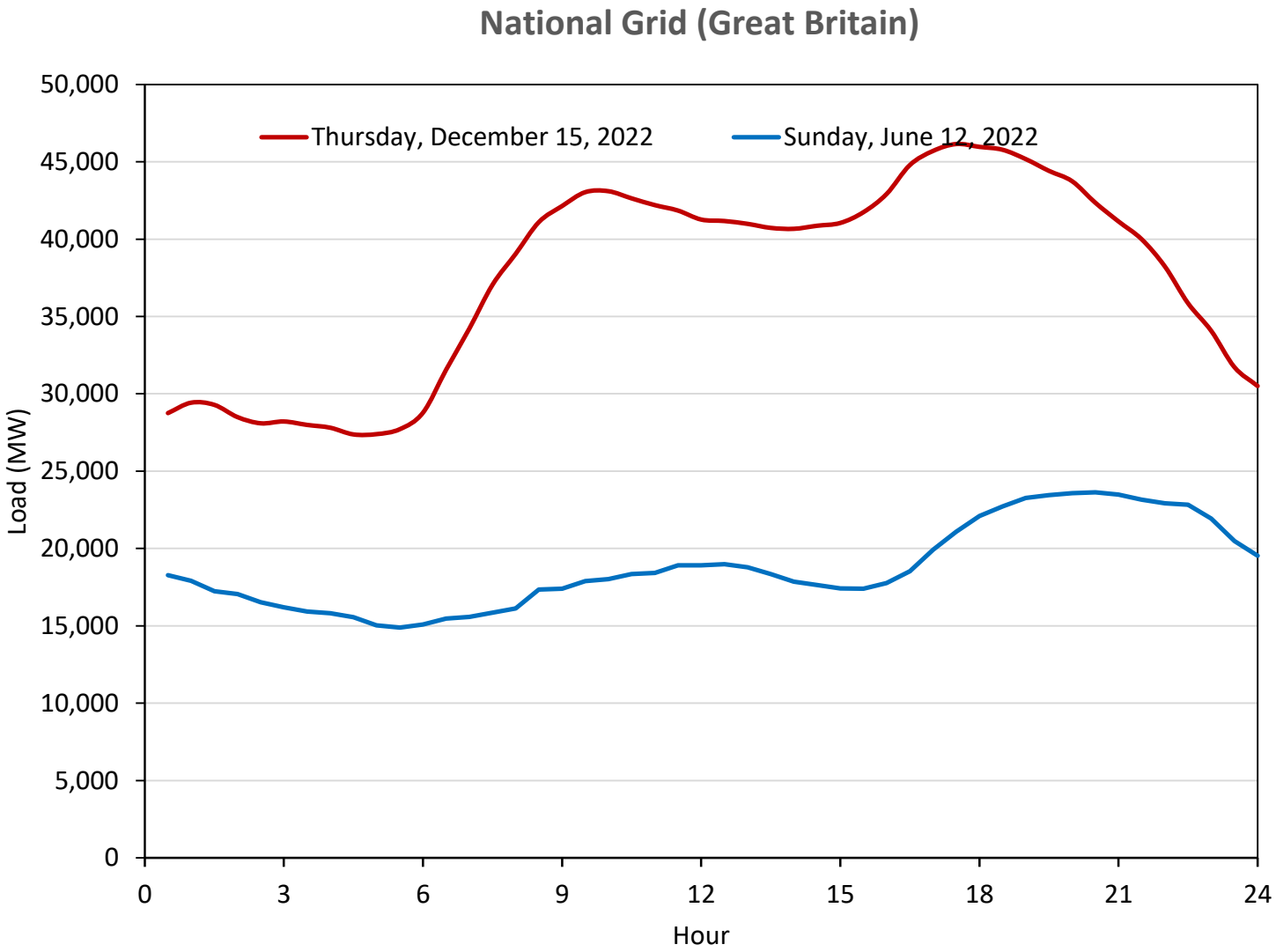
Changes in the average and peak load as a function of the average daily temperature for the ERCOT and PJM systems.

Source: Maximilian Auffhammer et al. PNAS
doi:10.1073/pnas.1613193114 © 2017
by National Academy of Sciences



Load profiles on the days with the highest and lowest loads in Great Britain

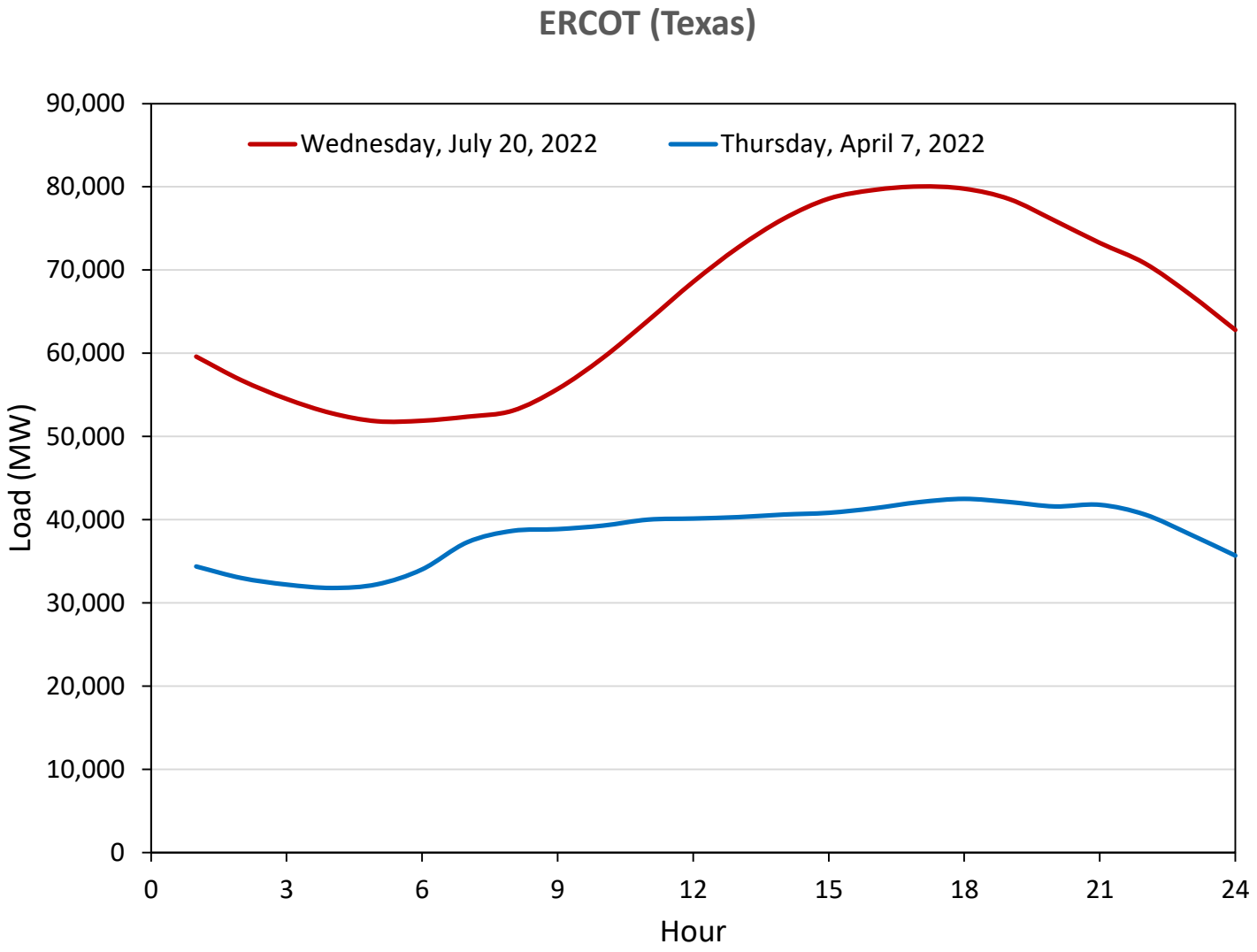
- Maximum and minimum temperatures in London
- December 15, 2022
  - 36°F (2°C)
  - 21°F (-6°C)
- June 12, 2022
  - 81°F (27°C)
  - 55°F (13°C)



Data: NGCESO

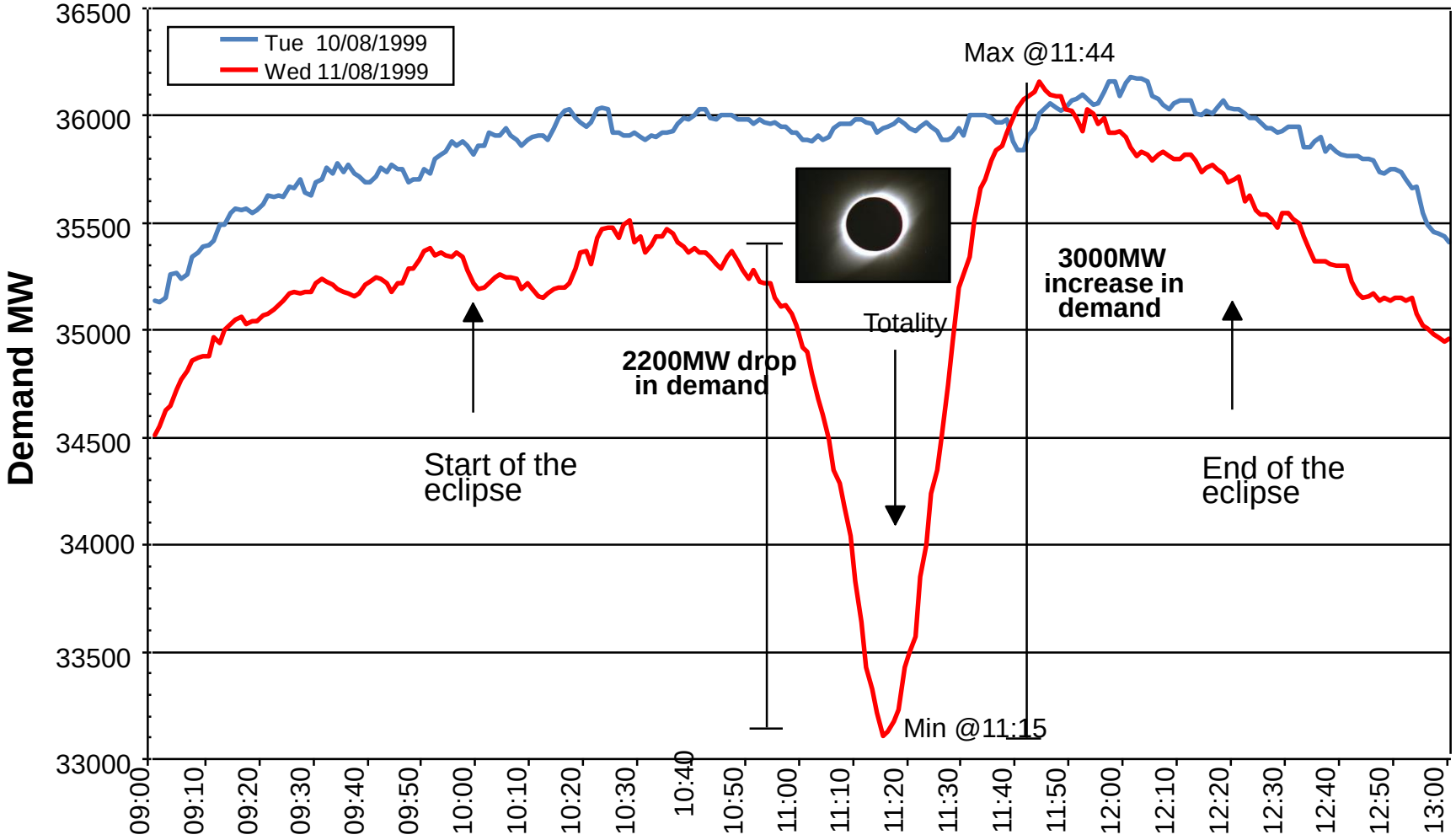
Load profiles on the days with the highest and lowest loads in Texas

- Maximum and minimum temperatures in Austin
- July 20, 2022
  - 103°F (40°C)
  - 74°F (23°C)
- April 7, 2022
  - 76°F (24°C)
  - 42°F(6°C)



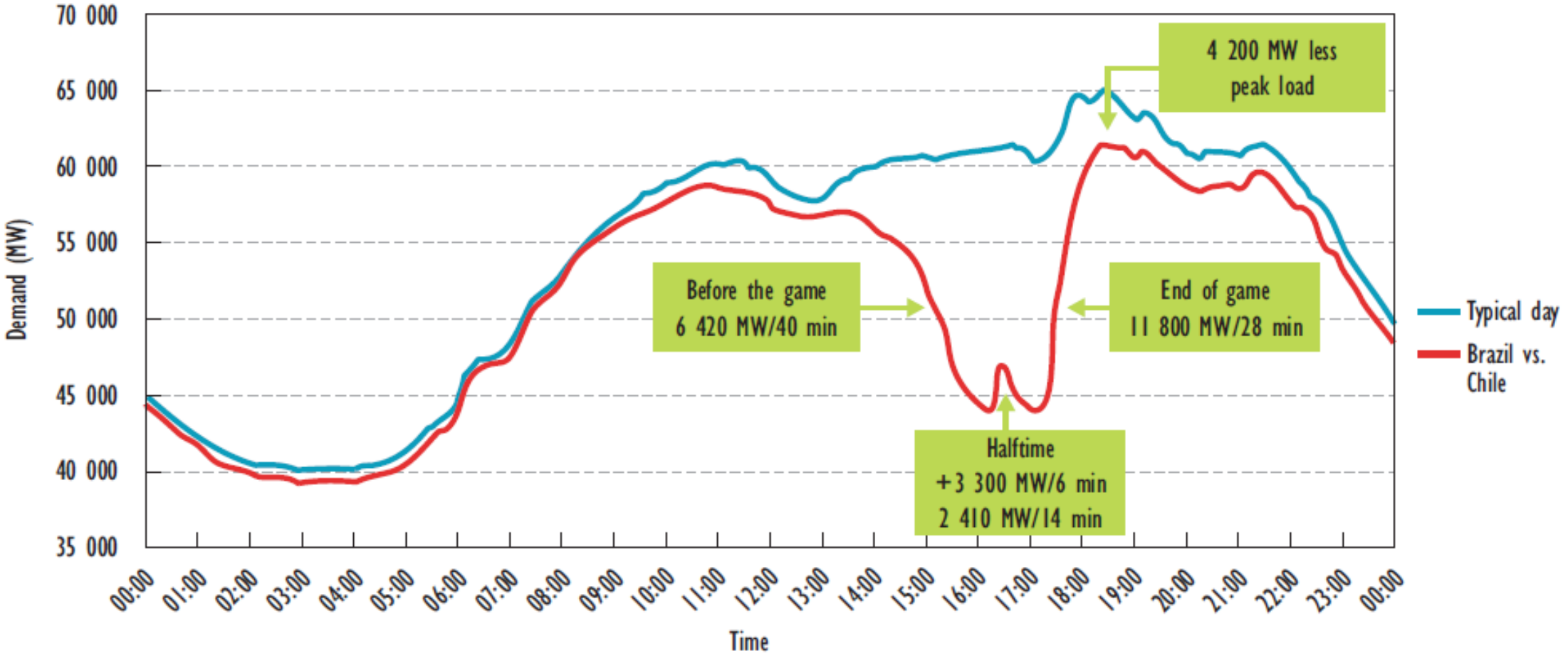
Data: ERCOT

Effect of the total solar eclipse on demand 11th August 1999 on the load in Great Britain



Data: National Grid

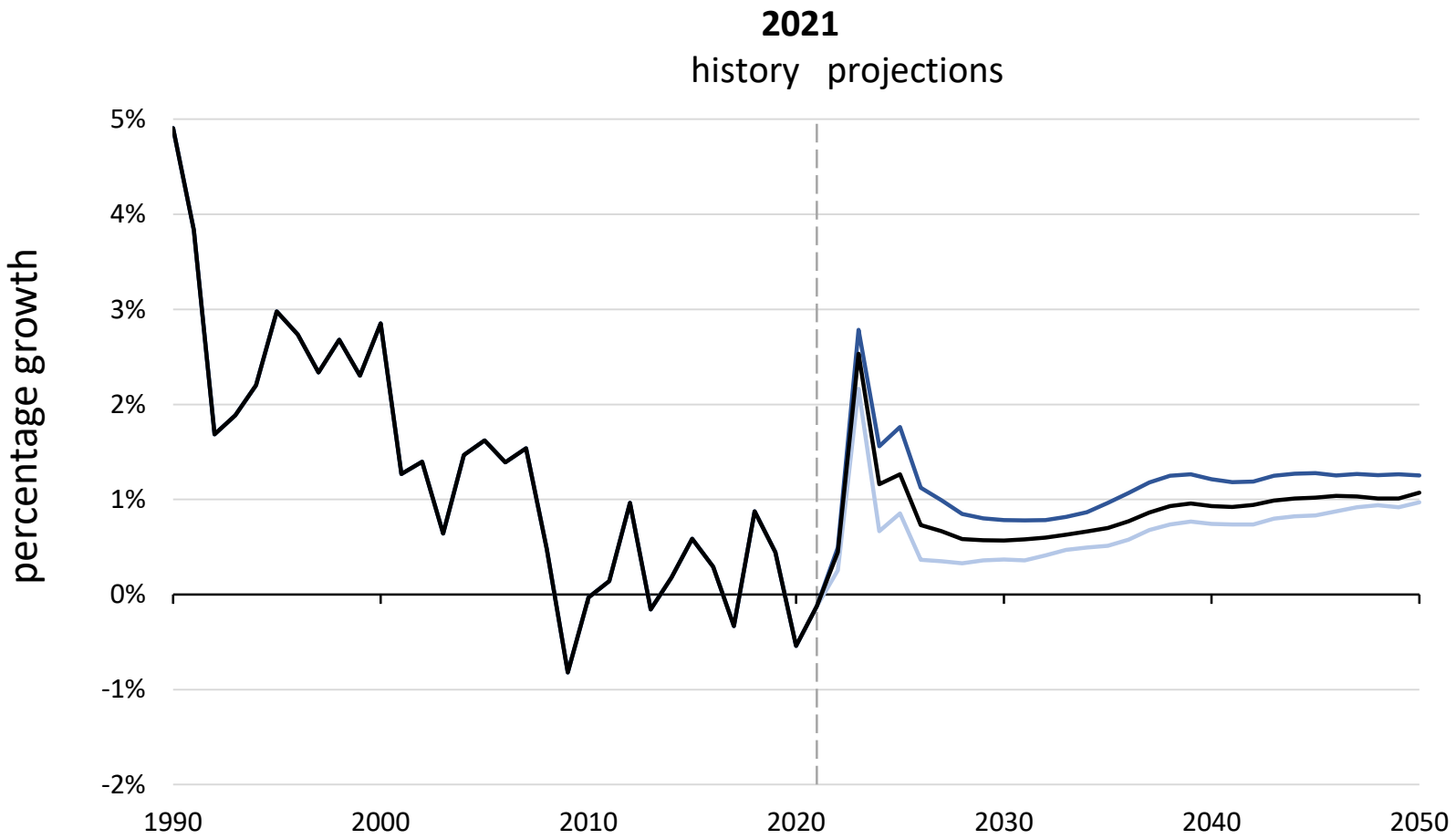
Brazil vs. Chile June 24, 2010



Long term effects on the demand

- Historically:
  - Consumption of electrical energy closely linked to economic activity
    - Increase in commercial and industrial demand
    - Household income grows → more appliances
- Since 2000, growth in electricity demand is slower than the growth in Gross Domestic Product (GDP)
  - Technological advances
    - Use of power electronics
  - Energy efficiency standards
    - Buildings, appliances
  - Structural shift in the economy
    - Less manufacturing, more services

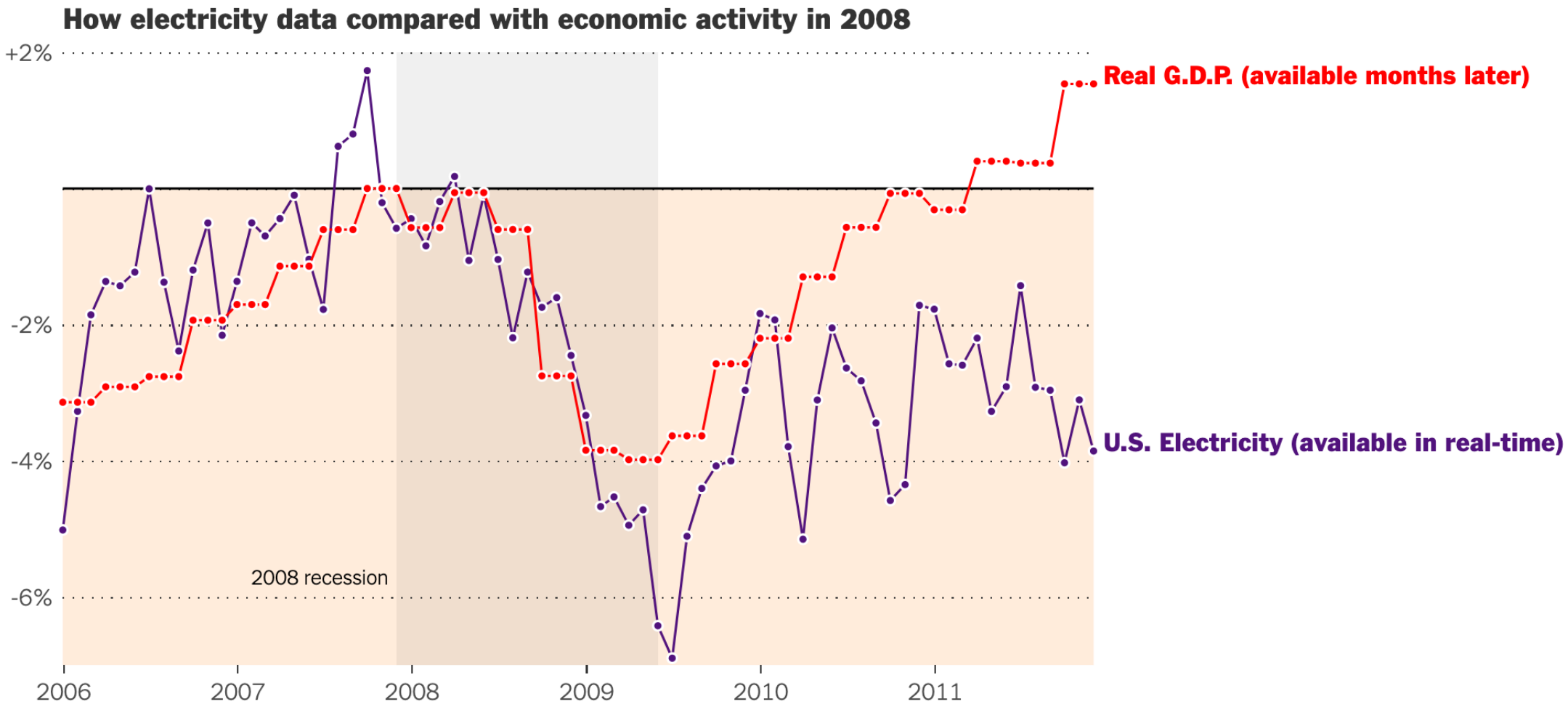
U.S. electricity use growth rate



Three-year rolling average
AEO2022 economic growth cases
High Economic Growth
Reference
Low Economic Growth

Source: Energy Information Agency – Annual Energy Outlook 2020

Electricity demand & economic activity

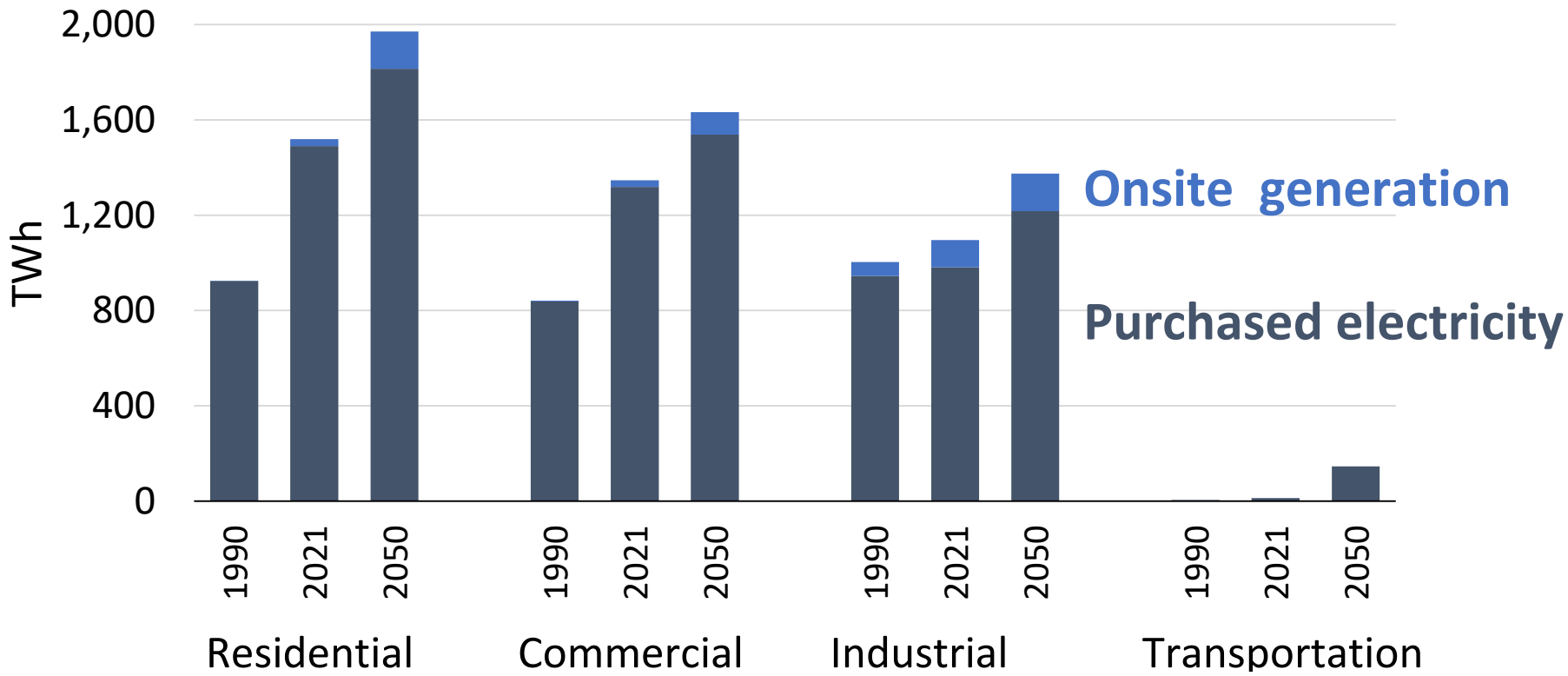


Source: NY Times

Long term forecasts

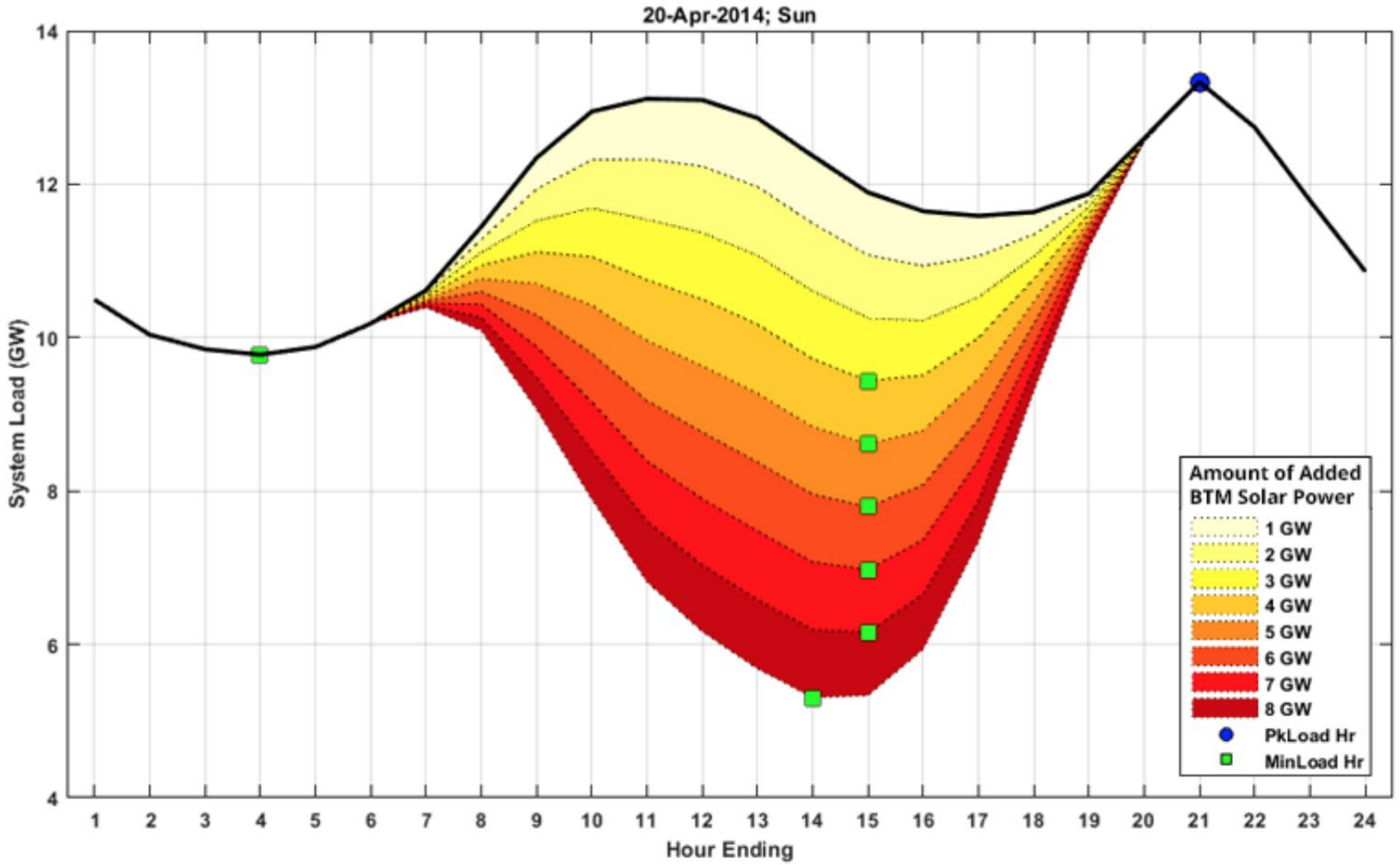
- Notoriously inaccurate
- Often completely wrong
- What factors make it even harder now?
  - Decarbonization of the economy
    - At what rate will transportation, heating be electrified?
  - Effect of climate change
    - Increased use of air conditioning
  - Increase in “behind the meter” generation
    - PV panels on residential rooftops

US electricity use by end-use sector



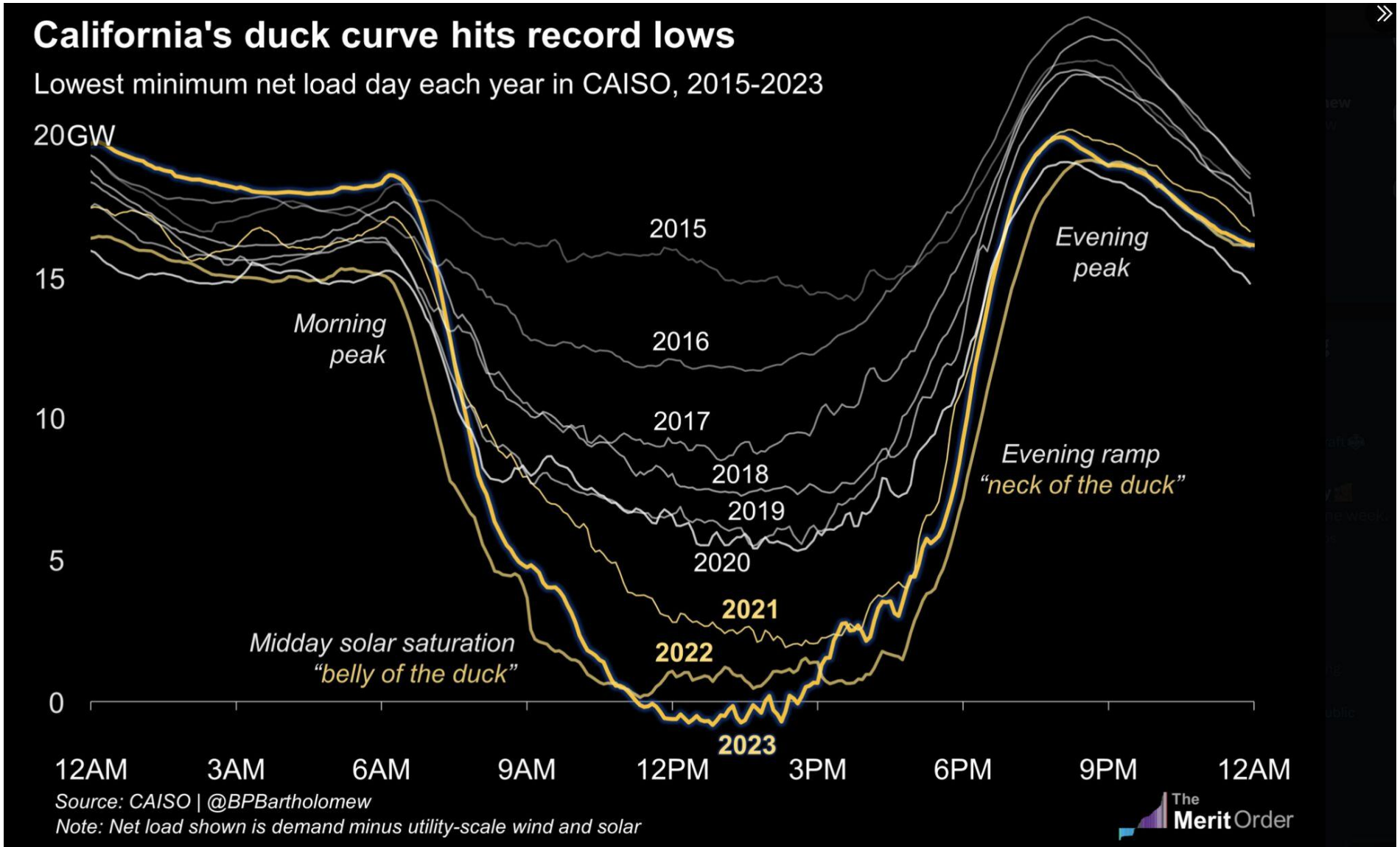
Source: Energy Information Agency – Annual Energy Outlook 2020 - AEO2022 Reference case

Effect of increasing amounts of behind-the-meter solar generation capacity on the shape of the system load for a typical spring day in New England

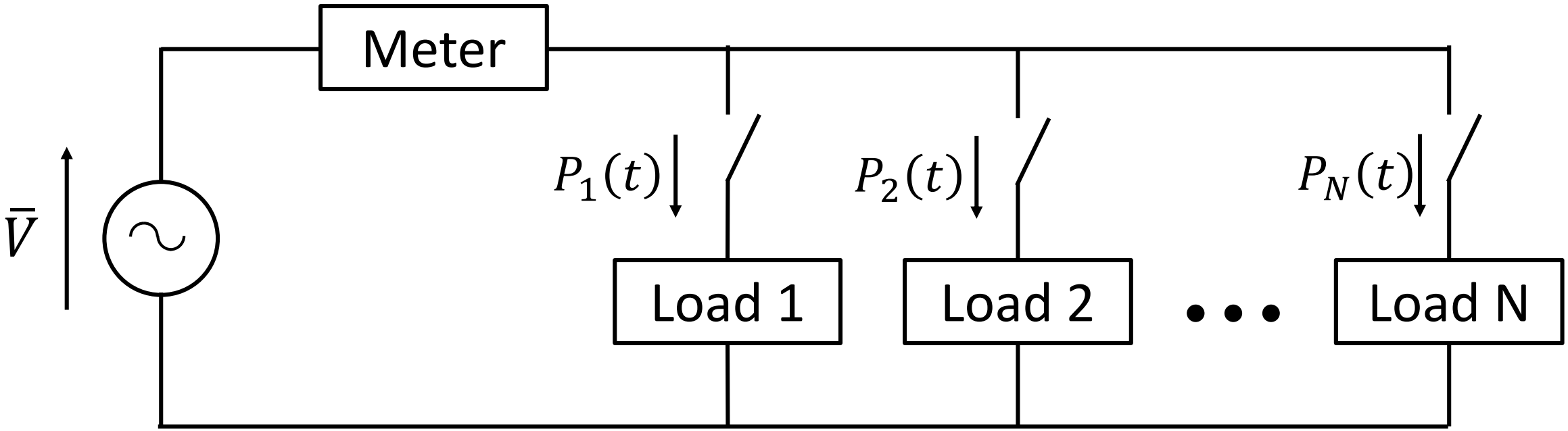


Source: ISO New England

The California “Duck Curve”



Metering and billing

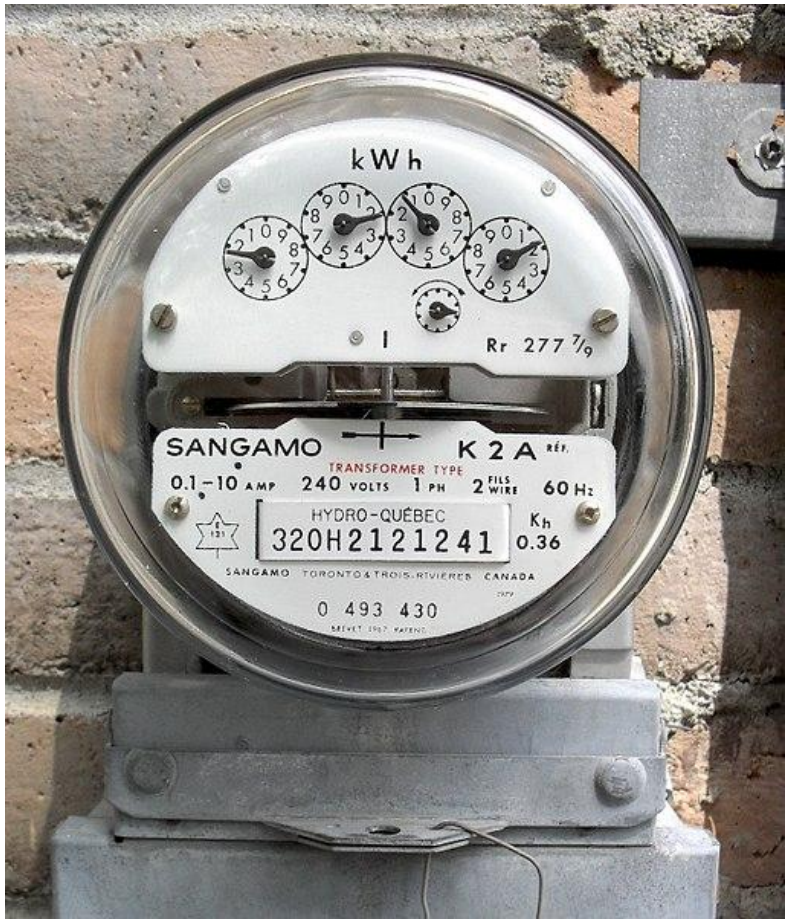


Electromechanical meter

- Measures only energy consumed
- Meter integrates mechanically the instantaneous active power

$$E = \int_{t}^{t+T} \left\{ \sum_{i=1}^{N} P_i(t) \right\} dt$$

- T: reading interval (typically one month)
- No charge for reactive power



“Smart” electronic meter



- Digital rather than mechanical integration
- Makes possible:
  - Remote reading
  - Remote disconnection
  - Remote outage detection

Electricity bill

- Residential and small commercial consumers:
  $$A = E \times c + FC$$
  - c: rate in \$/kWh
  - FC: fixed charge (\$)
  - A: total amount

- Larger commercial and industrial consumers:
  - Fixed charge (\$)
  - Energy charge (\$/kWh)
  - Peak demand charge (\$/kW_{peak})
  - Penalty for poor power factor

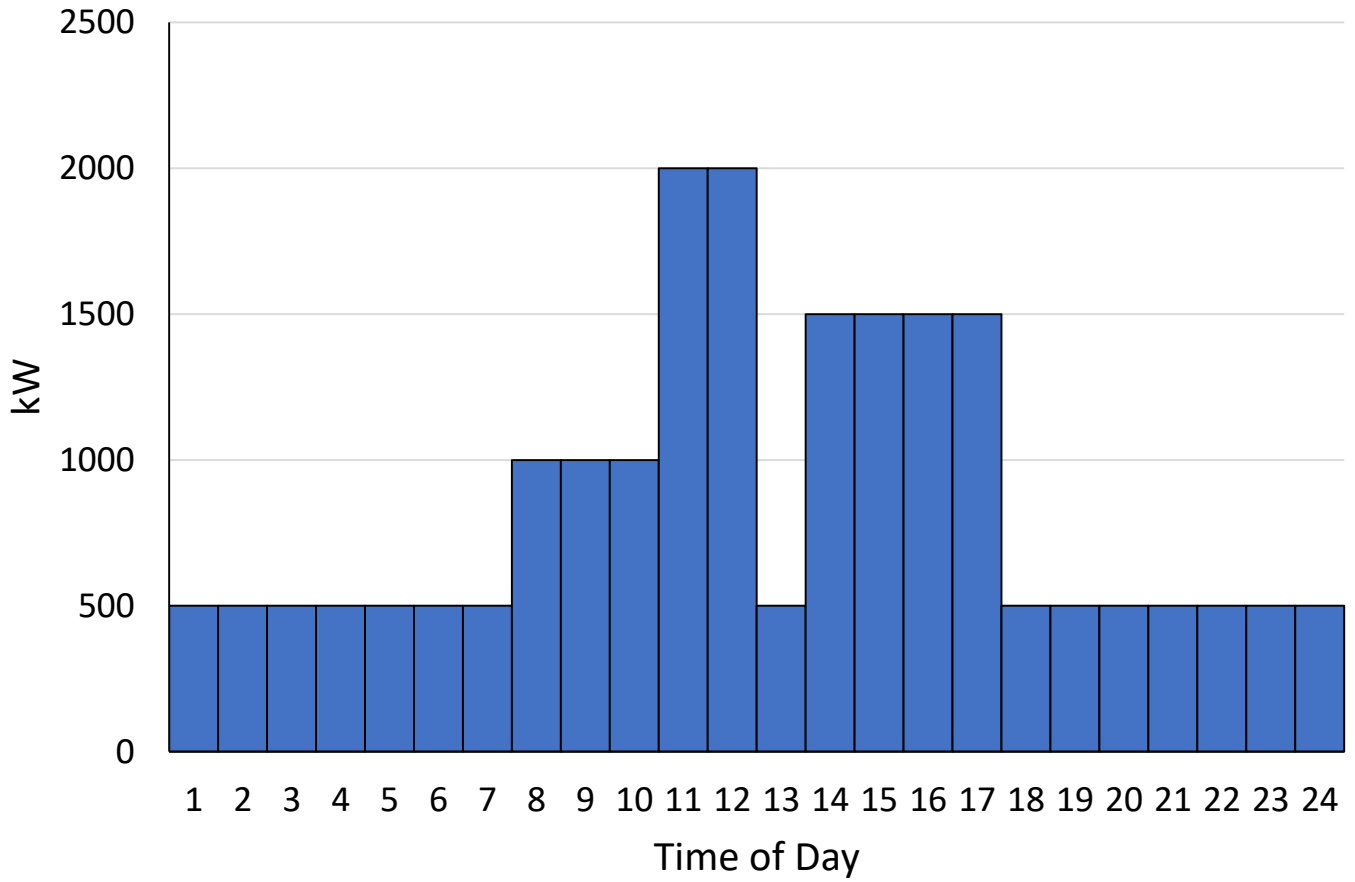
  - Requires a more expensive meter

Why charge for peak demand?

- The cost to the utility of supplying electricity is not just a function of the energy delivered
- The cost of the generating plants and the transmission and distribution networks is determined by the maximum amount of power that they have to produce or transmit.

Example 2.1

This figure shows the load profile of an industrial consumer.
Calculate the electricity bill for this day assuming that it is charged 0.12 $/kWh for energy, that it pays 0.75 $/kW for its peak load and that the standing charge is $15.



Example 2.1

- Total energy consumed:

$$E = 500 \times 15 + 1000 \times 3 + 2000 \times 2 + 1500 \times 4$$
$$= 20500 \text{ kWh}$$

- Peak load: $P^{max} = 2000\ kW$

- Daily electricity bill:

$$A = 20500 \times 0.12 + 2000 \times 0.75 + 15 = \$3975.00$$

Demand-side flexibility

- Consumers expect to get power when they flip the switch
- No energy storage → power produced must be equal to power consumed
- Power generation must follow demand
- Increasingly difficult and expensive as renewable generation increases
- Can the demand be more flexible?
  - Demand follows generation?
- Time of use tariffs:
  - Discourage consumption when generation is expensive
  - Encourage consumption when generation is cheap

Outages

- Local outages
  - Equipment failure
  - Accidents
  - Animals (squirrels, rats, crows,…)
  - Storms, earthquakes, hurricanes
- Wide-area outages (blackouts)
  - Imbalance or instability in the system
- Effect on individuals
  - Health, life
  - Inconvenience
- Effect on businesses
  - Economic losses

Quantifying the cost of outages

- Useful to estimate the value of countermeasures
- Impact of an outage depends on:
  - Vulnerability of individuals
    - Elderly vs. college students
  - Nature of the business
    - Restart industrial process
  - Timing of the outage
    - Rush hour vs. middle of the night vs. super bowl Sunday
  - Duration of the outage
  - Geographical extent
- A priori we can only get an estimated average cost

Value of Lost Load (VoLL)

- Estimated using surveys
- “How much would you be willing to pay to avoid an unexpected outage?”

→ Amount of money that an average consumer would be willing to pay to avoid not being able to consume a MWh of electrical energy

Value of Lost Load in different regions

- Spread of values illustrate how difficult it is to estimate VoLL
- VoLL is about two order of magnitude greater than cost of energy
- Shows that consumers value a reliable supply

Country/Region	VoLL ($/MWh)
United Kingdom	$22,000
Countries of the European Union	$12,290 - $29,050
United States	$7,500
MISO	$3,500
New Zealand	$41,269
Victoria - Australia	$44,438
Australia	$45,708
Ireland	$9,538
Northeast USA	$9,283-$13,925

Sources: London Economics, European Commission, Brattle Group, MISO. Where necessary, the values have been converted to US$

Complex power

- Lighting, heating loads → current in phase with the voltage

$$\bar{V} = V\angle 0°$$
$$\bar{I} = I\angle 0°$$

- Other loads (e.g., motors) → current lags the voltage

$$\bar{V} = V\angle 0°$$
$$\bar{I} = I\angle -\theta°$$

- Complex power:

$$\bar{S} = \bar{V}\bar{I}^{*} = V\angle 0°\, I\angle\theta° = V\, I\left(\cos\theta + jsin\theta\right) = VI\cos\theta + jVIsin\theta$$

$$\bar{S} = P + jQ$$

Active and reactive power

- Active power: $P = VI\cos\theta$
- Measures the rate at which electrical energy is consumed by the load and converted to another form of energy
- Units: W, kW, MW

- Reactive power: $Q = VI\sin\theta$
- Represents power that oscillates at twice the frequency of the voltage without being dissipated or put to practical use
- Dimensionally similar to active power
- Units: var (Volt Ampere reactive), kvar, Mvar

Apparent power

- The apparent power is the magnitude of the complex power:

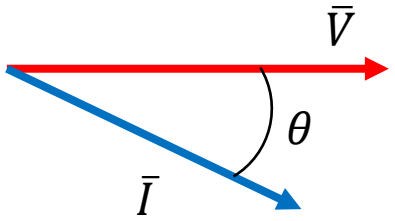
$$S = \left|\bar{S}\right| = \sqrt{P^2 + Q^2} = V\ I$$

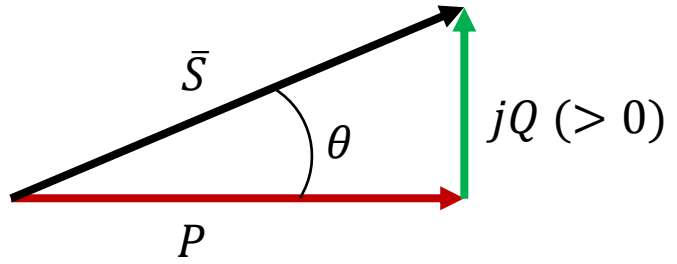
- Units: VA (Volt Ampere), kVA, MVA

Power factor and power triangles

$$pf = \frac{P}{\sqrt{P^2 + Q^2}} = \frac{P}{S} = cos\theta$$

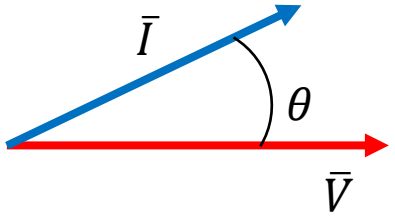
Lagging power factor:

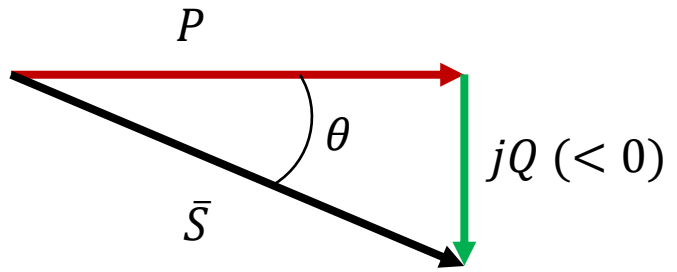




Load “consumes” reactive power

Leading power factor:





Load “produces” reactive power

Example 2.2: Complex power

A load is supplied by a 120 V source and draws a current of 5 A, which lags the voltage by 15°. Calculate the complex, active, reactive and apparent power supplied to this load, as well as its power factor.

$\bar{V} = 120\angle 0°$

$\bar{I} = 5\angle -15°$

$\bar{S} = \bar{V}\bar{I}^* = 120\angle 0° \times 5\angle 15° = 579.55 + j155.29\ VA$

$P = 579.55\ W$

$Q = 155.29\ var$

$S = 600\ VA$

$pf = \cos(15°) = 0.966$ lagging

Example 2.3: Complex power

A load supplied from a 240 V source consumes 100 W of active power and 50 var of reactive power. Calculate the complex and apparent powers drawn by this load, as well as its power factor and the magnitude and phase of the current.

$$\bar{S} = P + jQ = 100 + j50\ VA$$

$$S = |\bar{S}| = \sqrt{100^2 + 50^2} = 111.80\ VA$$

$$\theta = tan^{-1}\left(\frac{Q}{P}\right) = tan^{-1}\left(\frac{50}{100}\right) = 26.56°$$

$$pf = \cos(26.56°) = 0.894 \text{ lagging}$$

$$\bar{S} = \bar{V}\bar{I}^* \rightarrow \bar{I} = \frac{100 - j50}{240\angle 0°} = 0.466\angle -26.56°\ A$$

Example 2.4: Complex power

A load supplied from a 440 V source consumes 200 W at a lagging power factor of 0.9. Calculate the complex, reactive and apparent powers drawn by this load, as well as the magnitude and phase of the current.

$$pf = \cos\theta = 0.9 \rightarrow \theta = cos^{-1}(0.9) = 25.84°$$

$$Q = P\ tan\theta = 200\ \times \tan(25.84°) = 96.864\ var$$

$$\bar{S} = P + jQ = 200 + j96.864\ VA$$

$$S = |\bar{S}| = 222.22\ VA$$

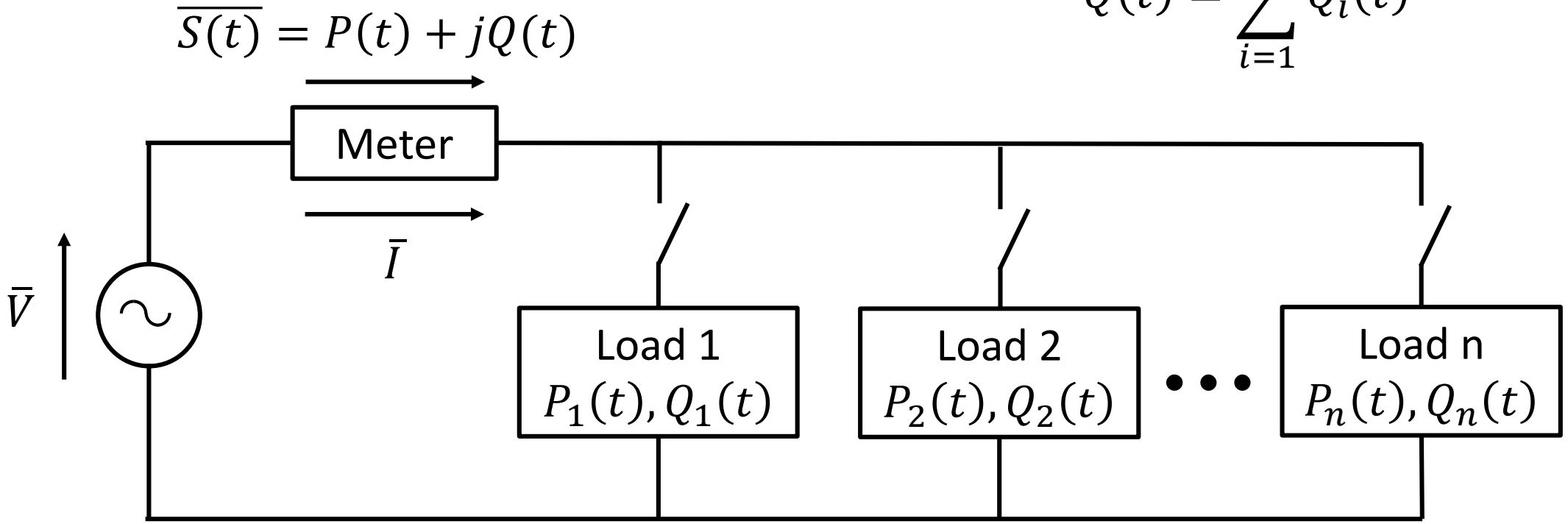
$$P = VIcos\theta \rightarrow I = \frac{200}{440 \times 0.9} = 0.505A$$

$$\bar{I} = I\angle -\theta° = 0.505\angle -25.84°$$

Parallel loads

$$P(t) = \sum_{i=1}^{N} P_i(t)$$

$$Q(t) = \sum_{i=1}^{N} Q_i(t)$$



Example 2.5: Parallel loads

Three loads are connected in parallel and supplied by an ideal 220 V voltage source:

L_1: 200 W at unity power factor

L_2: 400 W at 0.8 power factor lagging

L_3: 300 W at 0.9 power factor leading

Calculate the total active power, reactive power, complex power, apparent power and current supplied by this source, as well as the power factor of the aggregated load.

L_1: $P_1 = 200\,W, Q_1 = 0$

L_2: $P_2 = 400\,W, \theta_2 = cos^{-1}(0.8) = 36.87°, Q_2 = P_2 \times tan\theta_2 = 300\,VAr$

L_3: $P_2 = 300\,W, \theta_3 = -cos^{-1}(0.9) = -25.84°, Q_3 = P_3 \times tan\theta_3 = -145.3\,VAr$

Example 2.5: Parallel loads (continued)

$$P = P_1 + P_2 + P_3 = 900\ W$$

$$Q = Q_1 + Q_2 + Q_3 = 154.7\ VAr$$

$$\bar{S} = P + jQ = 900 + j154.7\ VA$$

$$S = |\bar{S}| = 913.2\ VA$$

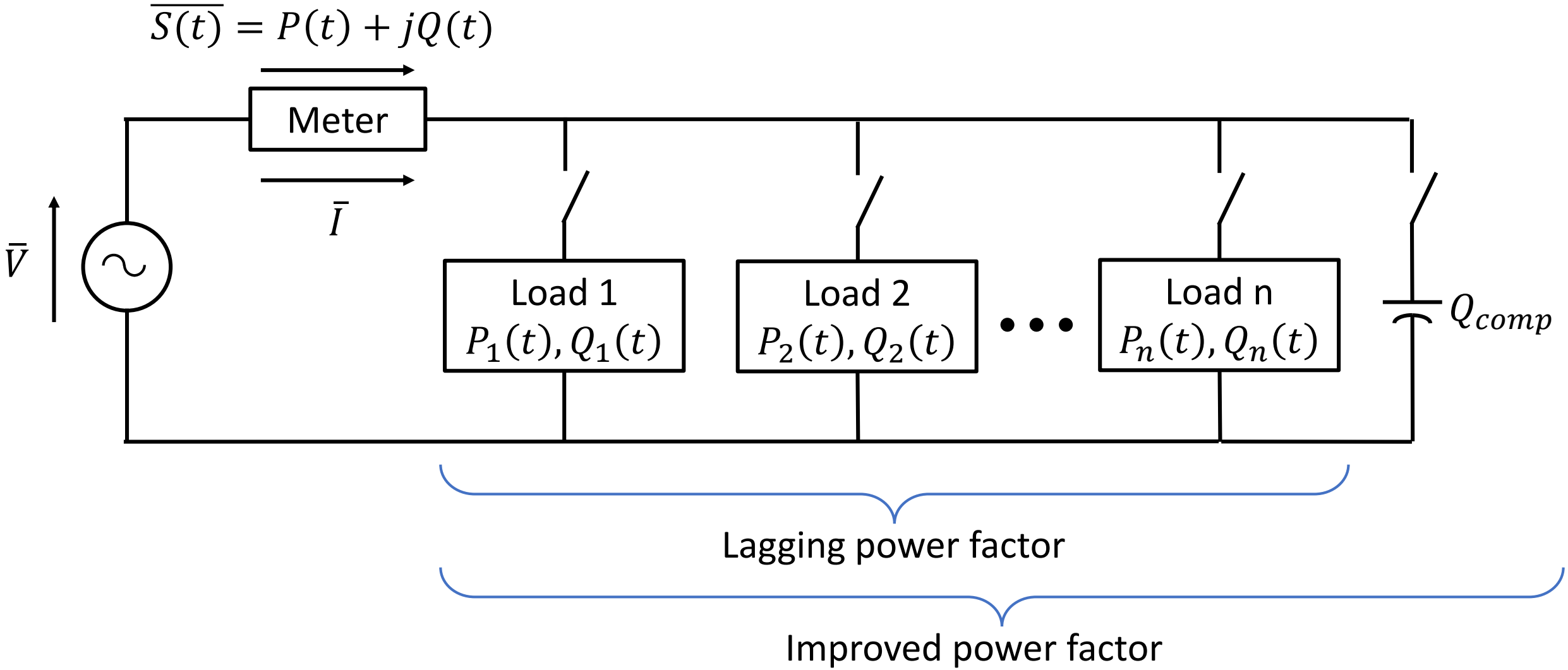
$$pf = \frac{P}{S} = 0.986$$

$$I = \frac{S}{V} = 4.15\ A$$

Reactive power

- Inductance forces the current to lag the voltage
  → lagging power factor
- Capacitance forces the current to lead the voltage
  →leading power factor
- Purely resistive load
  →unity power factor: $pf = cos\theta = 1.0$
  →No reactive power
  →All the current is put to practical use e.g., delivering active power
- Power factors close to 1.0 are thus desirable
- Large consumers are penalized if their power factor is lagging and too low
- Residential meters do not measure reactive power

Reactive power compensation



Example 2.6: Reactive power compensation

A load of 2 MW at 0.8 power factor lagging is supplied at 69 kV. Calculate the current that it draws from the source. Repeat this calculation for the case where this inductive load is compensated by a capacitive load of – 1 MVAr.

Uncompensated case:

$$pf = \cos\theta = 0.8 \rightarrow \theta = cos^{-1}(0.8) = 36.87°$$

$$Q_{unc} = P\ tan\theta = 2\ \times \tan(36.87°) = 1.5\ \text{Mvar}$$

$$S_{unc} = \frac{P}{\cos\theta} = 2.5\ \text{MVA}$$

$$I_{unc} = \frac{S_{unc}}{V} = 36.23\ \text{A}$$

Example 2.6: Reactive power compensation

A load of 2 MW at 0.8 power factor lagging is supplied at 69 kV. Calculate the current that it draws from the source. Repeat this calculation for the case where this inductive load is compensated by a capacitive load of – 1 MVAr.

Compensated case:

$$Q_{comp} = Q_{unc} + Q_{cap} = 1.5 - 1 = 0.5 \text{ Mvar}$$

$$S_{comp} = \sqrt{P^2 + Q_{comp}^2} = 2.06 \text{ MVA}$$

$$I_{comp} = \frac{S_{comp}}{V} = 29.88 \text{ A}$$

Reactive power compensation

