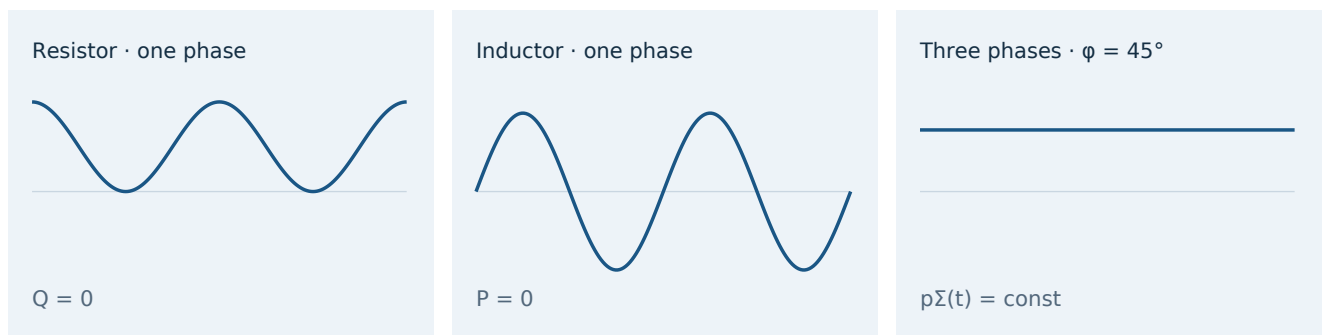


Reactive power: a debate about meaning

Difficult questions

Power engineering can still surprise us where the equations have been familiar for a century. An instrument displays kvar, equipment heats up, and a contract creates an obligation. What exactly has been measured? Why is it called power? Do a physicist, an engineer, a metrologist and a market participant mean the same thing?

This textbook grew out of questions about self-induction, pendulums, Tesla, resonance and payment for compensation. It helps readers test an explanation, reproduce a calculation and identify the evidence a transaction requires. Numerical examples are synthetic. Sources checked on 23 September 2026.



Edition 1.0 · 23 Sep 2026

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Two interactive calculations are available online: single- and three-phase instantaneous power, and compensation at constant active load. Their worked examples appear in chapters 2, 3 and 8 of this PDF.

1. One term, four different questions

A discussion of reactive power often changes its subject without saying so. It begins with energy stored in a field, moves to the calculated quantity Q , then to reducing cable current, and finally to the price of a service. Each statement can be reasonable within its own context. The difficulty arises when the transitions remain unexplained.

Level	Question	Evidence
Physics	How does field energy change and where does it go?	Energy balance, voltages and currents, field model
Circuit theory	How is Q defined for this operating condition?	Equation and explicit assumptions
Measurement	How did the instrument obtain its number?	Connection, algorithm, window, uncertainty
Economics	Who pays whom, and for what action?	Contract, settlement rule, accepted delivery

Electrodynamics makes testable predictions. Ways of reducing a complex process to one number can nevertheless differ. A standard establishes a useful, reproducible measurement convention. A theory explains selected properties of a system. A contract defines an obligation. Their consistency has to be established separately.

The question “does reactive power exist?” therefore needs clarification: does field-energy exchange occur; can Q be calculated; does the chosen indicator relate to additional current; is it accepted as a basis for payment? These are different questions. A dispute about terminology alone says little about whether a capacitor installation works.

2. Equations and their limits

Start with a single phase in sinusoidal steady state and the passive sign convention: positive power enters the load. U and I below are RMS values; φ is positive for lagging current.

Angular frequency is $\omega = 2\pi f$.

$$\begin{aligned} u(t) &= \sqrt{2} U \cos(\omega t); i(t) = \sqrt{2} I \cos(\omega t - \varphi) \\ p(t) &= u(t)i(t) = P + P \cos(2\omega t) + Q \sin(2\omega t) \\ P &= UI \cos \varphi; Q = UI \sin \varphi; S = UI; S^2 = P^2 + Q^2 \end{aligned}$$

Instantaneous power $p(t)$ describes the rate of energy transfer across the selected boundary. Its mean P gives net transfer over a period. P is positive for consumption and negative for regeneration under this convention. Active power can become mechanical work, heat, light or energy stored in a battery. The word “active” alone says nothing about usefulness or irreversibility.

Q is the coefficient of the quadrature term in this expression. Steady-state Q is constant and its average equals itself. The term $Q \sin(2\omega t)$ has zero mean. The amplitude of the complete oscillating part of $p(t)$ is S . Thus “ Q is the amplitude of power oscillation” needs qualification: which component, and under which model?

For an ideal resistor $\varphi = 0$ and $Q = 0$, yet $p(t)$ varies from zero to $2P$. Pulsating power alone does not establish energy return. For an ideal inductor $P = 0$ and $Q > 0$, and $p(t)$ does change sign. A pendulum is a useful analogy here: stored energy changes form periodically and losses require replenishment.

$$W_L = Li^2/2; W_C = Cu^2/2; Q_L = \omega LI^2; Q_C = -\omega CU^2$$

W is measured in joules and Q in var. For an individual ideal L or C under sinusoidal conditions, $|Q| = \omega W_{\max}$. The relation connects stored energy with exchange frequency. Increasing frequency can increase kvar for the same stored joules. It does not establish a universal conversion from kvar to kWh.

3. Two examples that challenge the usual picture

Three phases. Consider a balanced sinusoidal three-phase load. Phase voltages and currents are displaced by 120° . Adding the three $p(t)$ expressions cancels the double-frequency terms:

$$p_a(t) + p_b(t) + p_c(t) = 3U_{\text{phase}} I_{\text{phase}} \cos \varphi = P_{\text{total}}$$

Total instantaneous power is constant while $Q_{\text{total}} = 3U_{\text{phase}} I_{\text{phase}} \sin \varphi$ can be nonzero. For three identical ideal inductors, $P_{\text{total}} = 0$ and total stored magnetic energy is also constant. Exchange continues within each phase. The simple single-phase picture cannot be transferred unchanged to the combined three-phase boundary. The system boundary matters.

A switched resistor. An ideal resistor under symmetrical thyristor or triac phase control can draw a current whose fundamental lags the voltage. Q_1 is then nonzero, although $p(t) \geq 0$ and the ideal resistor stores no energy. Switching and waveform shape cause this result. Leszek Czarnecki discusses this class of counterexamples. [S4]

Both examples can be checked by calculation. They limit interpretations of Q based exclusively on energy returned to a source. That explanation remains useful for a particular single-phase LC circuit. A single picture cannot cover every instrument, operating condition and definition.

4. Could it have another name?

Calling everything self-induction is attractive because it returns the discussion to a mechanism. Self-induction links changing current, magnetic flux and induced EMF; a simple linear inductor has $e = -L \, di/dt$. But capacitive behaviour also exists, and a switched resistor can have nonzero Q_1 . The term therefore covers only part of the subject.

Name	What it helps explain	Where care is needed
Reactive power	Familiar engineering and contractual language	State the definition of Q
Quadrature power	Geometry of sinusoidal components	Specify frequency and aggregation for harmonics
Wattless power	Historical absence of mean power in an ideal reactive branch	Current still causes active losses in a real network
Field-energy exchange	Inductor and capacitor physics	A process description can correspond to several indicators
Amplitude of energy exchange	An intuitive simple oscillating system	Distinguish joules from watts; three-phase generalisation is limited
Nonactive power	The remainder outside P in a chosen decomposition	It may include distortion and unbalance and need not equal Q

These are editorial teaching explanations. The table attributes no invented terminology to researchers and announces no replacement standard. Technical documents can retain the accepted name while identifying the actual quantity, for example “fundamental reactive power Q_1 ”.

5. Who debated what?

The history is a history of changing tasks. Tesla worked with devices, phase relationships and oscillations. Later theories addressed increasingly complex conditions, while metrology sought reproducible definitions. The following are short paraphrases, without invented quotations.

Author or approach	Core contribution or position	What the reader should check
Nikola Tesla, 1891 and 1896	US464666A uses capacitance for phase displacement; US568179A describes charging and discharge involving self-induction. [S1] [S2]	Actual circuit, supply and measurement boundary
Charles Steinmetz	Symbolic AC calculation connects phase, impedance and a wattless component. [S3]	Sinusoidal assumptions and notation
Constantin Budeanu	Q_B sums signed reactive contributions across harmonics. [S5]	Contributions at different frequencies can cancel numerically while current remains
Stanisław Fryze	Current is decomposed into an active part proportional to voltage and an orthogonal remainder. [S5]	The remainder groups several causes of excess current
Akagi, Kanazawa and Nabae, 1984	Instantaneous p-q theory supports three-phase compensation control. [S6]	Its q and conventional Q have different definitions
Leszek Czarnecki, CPC	Physical current components; criticism of energy oscillation as a universal explanation of Q. [S4] [S7]	Distinguish reactivity, distortion and unbalance
R. Fetea and A. Petroianu	Identify confusion between mean and amplitude and discuss abandoning the name reactive power. [S8]	Read the conclusions with their model assumptions
Gaunt, Chisepo and Malengret, GPT	Propose a system model including losses, unbalance and distortion; challenge conventional physical interpretations of Q. [S9]	An argued author position within an ongoing debate
IEEE and IEC	Standardise definitions and measurement requirements. IEEE 1459-2025 superseded the 2010 edition; IEC 62053-24:2020 addresses fundamental components. [S10] [S11]	Edition, scope and the actual instrument method

The participants do not form two simple camps. Someone may criticise a quantity's physical interpretation while using it for control. An effective compensation algorithm can still raise questions about generalisation. Publication in a CIGRE journal alone does not make an article's conclusions an organisation-wide standard.

Earlier discussions also raised a remark attributed to Colin Schauder about the name being misleading. A reliable primary source for that particular wording was not established in the checked material, so it is not presented here as a quotation. Attractive attributions deserve the same verification as equations.

6. Harmonics: one triangle is insufficient

For periodic nonsinusoidal signals, average active power is the sum over matching frequencies: $P = \sum U_h I_h \cos \varphi_h$, with any DC component accounted for correctly. In a single-phase circuit $S = U_{\text{rms}} I_{\text{rms}}$. P/S defines power factor PF for consumption. The cosine of φ_1 applies only to the fundamental.

Budeanu's approach gives $Q_B = \sum U_h I_h \sin \varphi_h$. Positive and negative contributions at different frequencies can cancel. $N = \sqrt{S^2 - P^2}$ describes the complete nonactive remainder for the selected S . Q_B , Q_1 and N generally differ. The simple identity $S^2 = P^2 + Q^2$ requires checking its assumptions.

Synthetic example: voltage has only a fundamental $U_1 = 230$ V. Fundamental current $I_1 = 10$ A is in phase with it; fifth-harmonic current $I_5 = 5$ A. Then:

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I_rms = √(10² + 5²) = 11.18 A
P = 2,300 W; Q₁ = Q_B = 0
S = 2,571.5 VA; PF = 0.8944; N = 1,150 VA
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An instrument calculating Q_1 displays zero. One labelling $\sqrt{S^2 - P^2}$ as Q displays 1,150. Under that label, the second instrument uses a different indicator. Comparing the numbers without the measurement manuals is uninformative. The additional current and heating are real.

With sinusoidal voltage, the current may still contain higher harmonics. If the current has no DC component, $PF = \cos \varphi_1 / \sqrt{1 + THD_I^2}$. With $\cos \varphi_1 = 1$ and $THD_I = 50\%$, PF again equals 0.8944. A capacitor bank selected from $\cos \varphi_1$ alone does not solve this problem. [S12]

7. What the meter actually measures

A digital instrument samples voltage and current, processes them and outputs calculated indicators. P requires time-aligned products u·i. For Q it uses a selected procedure: fundamental extraction, spectral summation, quadrature processing or another algorithm. A “true RMS” label does not specify its Q algorithm.

IEC 62053-24:2020 explicitly links its conventional reactive energy to the fundamental voltage and current components. It covers the relevant meters and their type tests. It does not impose a single definition on every research analyser. [S11]

A quarter-period delay gives a 90° shift only at the fundamental. At harmonic h the shift is $h \cdot 90^\circ$. A simple T/4 delay and an equal quadrature shift of every harmonic therefore give different results. Filters, the observation window and nonstationarity also affect estimates.

Protocol field	What to record
Boundary	Site inlet, feeder, motor terminals or LC branch
Quantity	P, Q ₁ , Q _B , N and defined S; PF and $\cos \varphi_1$ separately
Connection	Three/four wires, phase assignment, CT/VT direction and ratios
Time	Sampling rate or documented method, averaging window, time zone
Quality	Harmonics, unbalance, voltage range, missing data
Signs	P and Q directions, quadrants and exact registers
Traceability	Model, firmware, verification/calibration and uncertainty

A kvarh register accumulates the time integral of the contractually selected Q. It can increase while an ideal reactive branch has zero mean active power. This record characterises operation over an interval; it does not equal an energy stock available for later extraction. Quadrant meanings and register aggregation must be checked against the meter documentation.

8. What compensation delivers: a worked calculation

Assume a balanced sinusoidal three-phase load consumes $P = 700$ kW at 400 V line-to-line. Power factor changes from 0.80 to 0.95. Useful active load and voltage remain constant. All values are synthetic.

Quantity	Before	After
Active power P	700 kW	700 kW
Apparent power $S = P/PF$	875.00 kVA	736.84 kVA
Reactive power $Q = P \tan(\arccos PF)$	525.00 kvar	230.08 kvar
Line current $I = P/(\sqrt{3} U_{LL} PF)$	1,262.95 A	1,063.54 A

Required compensation Q_c is about 294.92 kvar. Apparent power falls by 138.16 kVA and current by 15.79%. For the same resistance, I^2R losses in the relieved section fall to $(0.80/0.95)^2 = 0.7091$ of their previous value, a reduction of 29.09%.

Now define the saving boundary. Suppose this particular section initially loses 30 kW. Afterwards it loses 21.27 kW, giving a gross benefit of 8.73 kW. If the compensator consumes 0.50 kW, the net benefit is 8.23 kW. Over 6,000 identical hours this is approximately 49.35 MWh. Initial losses and operating hours are exercise inputs; a project must substantiate them.

The 29.09% applies to the selected section's losses. It does not establish an equivalent percentage reduction in whole-site consumption. Lower kVA also does not automatically confer a contractual right to additional kW. Equipment, temperature, load profile, protection, voltage quality and connection documents constrain additional load.

Location changes the outcome. Compensation at the motor relieves more of its supply path. A common bank at the inlet reduces upstream current while currents in individual outgoing feeders remain. Selection using Q_c alone still requires harmonic, switching and resonance checks. [S13]

9. Voltage, location and inverter capability

In a simplified radial-line model, voltage change depends on $R \cdot P + X \cdot Q$. The reactive term is often particularly significant in high-voltage networks; low-voltage resistance makes P influential too. Direction, magnitude and permissible action depend on the actual circuit and operating condition.

One Mvar at different nodes provides different value. A service must specify its node, voltage range, response time, duration and available control directions. Adding the nameplate kvar of every store does not establish a guaranteed resource at an arbitrary network node.

For an idealised inverter: $P^2 + Q^2 \leq S_{\text{rated}}^2$

At 80 kW, a 100 kVA inverter has a geometric $|Q|$ limit of 60 kvar. At 100 kW it has no such headroom in this model. Actual limits depend on current, temperature, DC-link voltage, controls and equipment specifications. Some devices can regulate Q near $P = 0$ if their design and operating mode permit it; active losses remain.

Q availability, active-power reserve, battery charging and active-energy delivery can therefore compete for the same current limits. Compatibility must be calculated for each interval. Research on distributed-inverter Q control explicitly considers these network constraints. [S14]

10. Tesla, resonance and very large kvar

Resonance can produce high branch current and high component voltage with relatively little input power covering losses. Understanding an experiment requires simultaneous attention to external active input, reactive quantities in individual branches and stored energy. A patent or a striking demonstration cannot replace that balance.

In a synthetic series RLC model, frequency is 1,000 Hz, RMS current is 50 A, and both inductor and capacitor voltages are 1,000 V. Thus $|Q_L| = |Q_C| = 50,000$ var. Each reactance has magnitude $20\ \Omega$; $L \approx 3.183$ mH and $C \approx 7.958$ μ F. At resonance, $Q_L + Q_C = 0$ at the external boundary despite the large branch quantities.

$$E = |Q_L|/\omega \approx 7.96\text{ J}$$

$$\text{Quality factor } q_f = \omega E/P_{\text{loss}} = 100 \rightarrow P_{\text{loss}} = 500\text{ W}$$

Here q_f is dimensionless quality factor and Q_L is measured in var. They are different quantities. Adding 5 kW of useful extraction while maintaining the original stored energy and amplitudes requires approximately 5.5 kW of input under the stated loss model. Without replenishment, 7.96 J could supply 5 kW for at most about 1.59 ms, even neglecting losses.

The ratio of 50 kvar to 0.5 kW is therefore not an efficiency of 10,000%. It compares oscillation intensity with loss. Testing an unusual-generator claim requires integrated input and output active energy, changes in all stored energy, all electrical and mechanical inputs, and independent reproduction. Regenerative braking is also evaluated through active-energy balance; the sign of Q does not determine it.

11. Who pays whom?

Payments can cover equipment, maintenance, compliance with operating conditions, control availability or verified results. “Reactive power compensation” in a commercial proposal does not by itself identify the purchased product.

Situation	Payment direction	What is purchased
Installation and service	Asset owner → contractor	Equipment, installation, maintenance or an agreed result
Russian network transmission	Customer → network operator, possibly through a supplier	Clause 16 of the rules under Resolution 861 provides coefficients for specified breaches or agreed regulation; applicability requires checking the contract, procedure and methodology. [S15]
Russian system service	SO UPS → selected provider	Q regulation by generating equipment without active-energy production under the relevant service arrangement. [S16]
Great Britain, ORPS	NESO → eligible service provider	Contracted utilisation; the published mechanism includes £/Mvarh payments. [S17]
Serbia	Customer → supplier under the applicable bill	EPS distinguishes reactive and excessive reactive energy, with the excess threshold linked to $\cos \varphi = 0.95$. [S18]

A customer can incur costs for its operating behaviour while a participant in another contractual arrangement earns revenue for voltage control. A financial model must first establish the asset’s role and applicable rules. This textbook does not model current tariffs or promise returns.

There is no universal physical number of lines on an electricity bill. Energy, capacity settlement, network service, supply charges, adjustments and separate services may be grouped differently. Line count does not equal the number of tradable rights. For each additional service, check customer agreement, deliverable, acceptance and whether the same obligation has already been included in another charge.

12. What can be tokenised?

The useful starting point is a specific enforceable right linked to a measurable service or verified receivable. A kvar number alone identifies neither debtor, owner nor performance conditions. The educational structures below require their own legal implementation in the chosen jurisdiction.

Structure	Unit and evidence	Essential condition
Regulation availability	Available kvar range over an interval, readiness test	Node, direction, response time and constraints specified
Delivered regulation	kvarh under an agreed algorithm, instruction and telemetry	Payable intervals and acceptance criteria defined
Active-loss savings	kWh after normalisation and compensator consumption	Boundary, baseline model and uncertainty agreed
Right to a share of revenue	Monetary amount of an accepted service	Payer, claim basis and due date identified
Access to released headroom	Verified permissible load at a specific node	Physical limit and right of use established

Kvar defined by one frequency scope and algorithm cannot silently be pooled with another interpretation. “Free kVA”, “saved kWh” and “reserved kW” require different checks. One installation can produce several benefits, but each needs an independent basis for accounting.

Selling Q availability and active reserve from the same inverter requires a compatible P-Q envelope. Repeated assignment of one receivable requires checking rights and encumbrances; describing one physical benefit under several labels requires checking the methodology. A registry should retain provenance and already allocated shares.

13. A result passport and a synthetic transaction

A minimum passport is needed before pricing. It lets another engineer reproduce the calculation and another party understand the obligation.

1. Asset identifier, circuit and measurement point.
2. Quantity and unit: Q_1 , Q_B , N, PF, kvarh or kWh.
3. Standard, edition, instrument algorithm, observation window and signs.
4. Load profile, voltage, harmonics, unbalance and validity conditions.
5. Instruments, transformation ratios, uncertainty and missing data.
6. Baseline model, intervention and testable causality when savings are paid.
7. P-Q envelope, availability, instructions, constraints and acceptance.
8. Right, holder, obligated party, term and payment formula.
9. Independent verification, underlying data and statement version.
10. Allocation, service compatibility and protection against double counting.

Synthetic example SYN-Q-001. Availability of ± 100 kvar is accepted at SYN-NODE-A for four hours with $|P| \leq 50$ kW. The inverter is rated 125 kVA. In the idealised circle, $\sqrt{(50^2 + 100^2)} \approx 111.8$ kVA, so the commitment passes this geometric check only. Voltage, temperature, specifications and the instruction still require verification.

Assume the exercise contract pays 2 currency units per kvar-hour of availability, counting only one agreed 100 kvar direction. Gross payment is $100 \times 4 \times 2 = 800$. A symmetrical ± 100 range does not automatically double the volume. Acceptance and contractual terms determine whether a receivable arises. The price is invented and is not a market quotation.

A different contract paying actual utilisation could produce another amount or zero over the same four hours. A token description should therefore identify the product and status: declared, reserved, delivered, accepted or paid. Changing the Q algorithm requires a new version and an agreed transition between datasets.

14. Designing a convincing experiment

For a compensation study, first fix the circuit, measurement points and load state. Record $u(t)$, $i(t)$, P , the selected Q , RMS values, harmonics and temperatures synchronously.

Compare matched intervals with and without compensation; the switching sequence helps distinguish the intervention from ordinary operating changes.

Include compensator consumption and changes in stored energy. Phase-angle uncertainty is particularly significant when a small Q is measured against a large S . Before claiming an effect, verify phase assignment, CT saturation, timing and instrument algorithms. More displayed decimal places do not create greater accuracy.

For resonance experiments, measure separately at the input, output and circuit elements. Integrate active energy over a window containing startup, steady operation and shutdown, or account separately for initial and final stored energy. Comparing a voltage peak with an averaged input-power reading is unsuitable for an energy balance.

A good protocol states in advance which outcome would support a hypothesis and which would reject it. Qualified personnel should perform measurement and switching on live power installations using appropriate protection. The educational plots on this page can be explored without connecting anything to the grid.

15. Questions to check your understanding

- 1. A meter shows $Q_1 = 0$ and $PF = 0.89$. A contradiction?** No. Check harmonics and unbalance, then the definitions of S and PF. Chapter 6 produces this condition through current distortion.
- 2. Q is unchanged after installing a filter. No benefit?** One Q reading is insufficient. Harmonics, RMS current, losses, voltage or permissible loading may have changed. Each result needs its own indicator.
- 3. At resonance the inductor has 50 kvar and the source supplies 500 W. Where is the remainder?** These numbers do not define a subtractable remainder. The branch exchanges energy and the source covers losses; capacitor Q can cancel inductor Q at the input boundary.
- 4. Can Q be replaced by “self-induction”?** The term describes a mechanism in an inductor. The wider subject also includes capacitance, switching, harmonics and the chosen calculation algorithm.
- 5. Line losses fall by 29%. Does the whole bill fall as much?** In chapter 8 the percentage applies to assumed losses of 30 kW. Billing depends on the measurement boundary and payment structure.
- 6. Do four hours of ± 100 kvar readiness give 800 kvarh?** Only if the contract counts both directions that way. SYN-Q-001 settles 400 kvar-hours of availability; actual utilisation may differ.
- 7. Two researchers use different Q quantities. Who is wrong?** First compare tasks, definitions and assumptions. Different indicators can be valid. An error arises from an invalid conclusion or application outside a formula's domain.
- 8. Does zero mean energy transfer imply a worthless service?** No. Equipment occupies current capacity, has losses and can provide useful voltage regulation. Price follows the accepted service and contract.

16. What remains open?

Sinusoidal calculation is simple and reproducible. The interesting questions start with distortion, switching, unbalance and boundary selection. Which indicator best predicts avoidable losses? How should a terminal calculation relate to the behaviour of the whole network? How can data from different meter generations be combined? How should a local service be valued while distinguishing capability from delivery?

There is room for new algorithms, research and products. Each benefits from clear definitions and open testing. Wonder about power engineering becomes productive when a question leads to a circuit, data, a calculation and an experiment someone else can repeat.

The textbook's working rule: before pricing one kvar, record exactly which kvar is measured, where, when, by which method, and what obligation is attached to it.

Sources and verification scope

Researchers' positions are attributed to their authors. S10 and S11: official standard records and descriptions checked; full normative text is not reproduced. S6: bibliography and abstract checked. S15: legislation reproduced in a legal reference system. Sources retain their original language. Teaching conclusions, diagrams and calculations are editorial work.

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