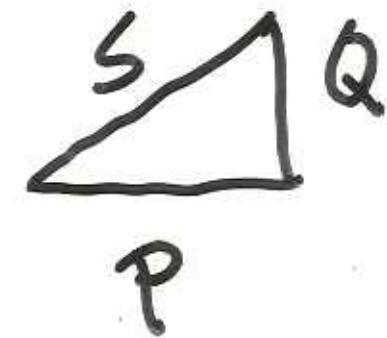
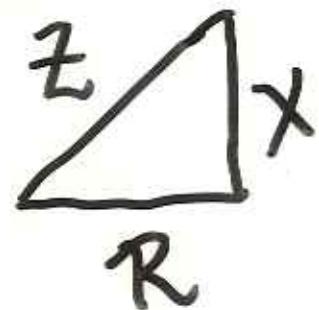


CHAPTER 7

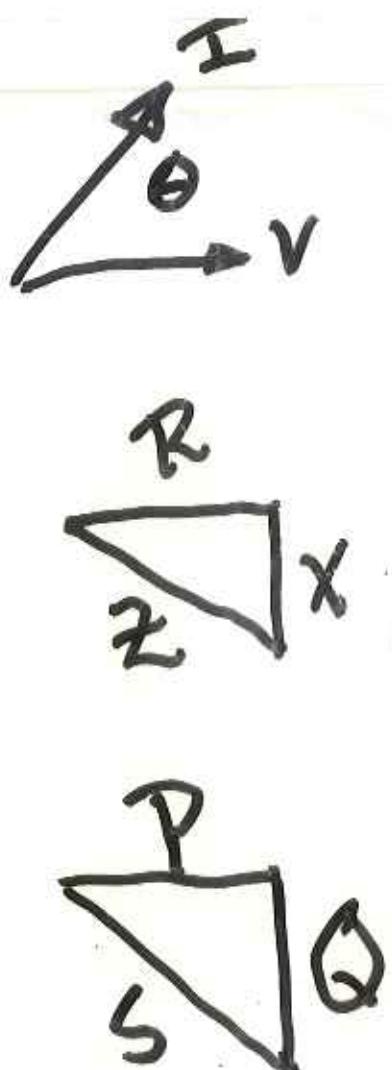
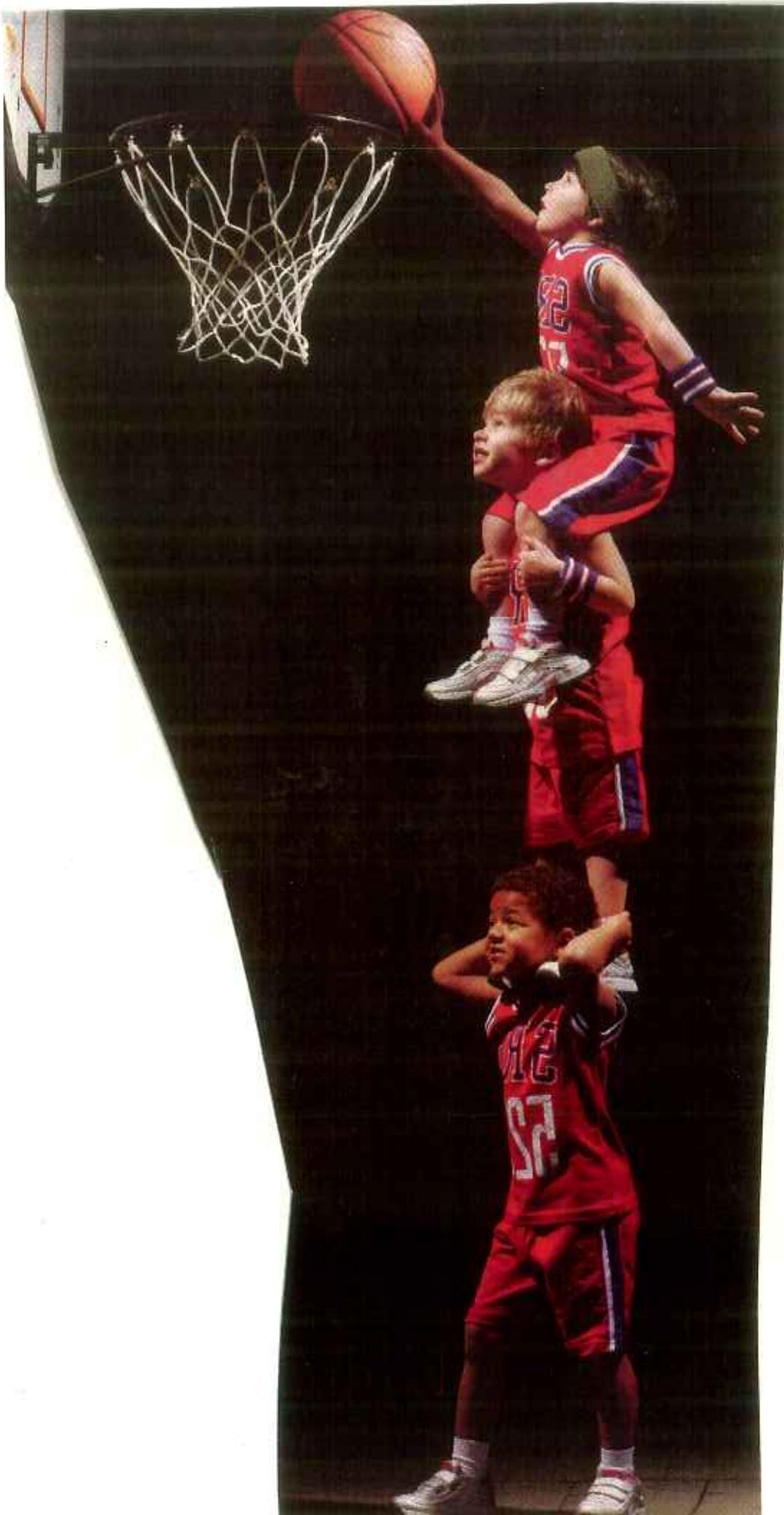
Active and Reactive Power

Read now!

In electric power technology, the terms active, reactive and apparent power constantly crop up. The reason is that they facilitate the understanding of power flow in ac machines, transformers, transmission lines, and electronic converters. The ingenious power triangle method of solving ac circuits is also revealed (Section 7.17). At an intermediate level, the notion of conjugate current is used to determine the active and reactive components of power by vector algebra (Section 7.18).



Units



- ② Transmission
- ① Generation
- ③ Distribution

North American Power Grid

Interconnected transmission

- 100 (varies) – 750 kV
- High Voltage DC
- 3 A-synchronous areas

Radial distribution

- 2.4 – 34.5 kV

P Governed by:

flow

① Kirchoffs laws

② Contract law

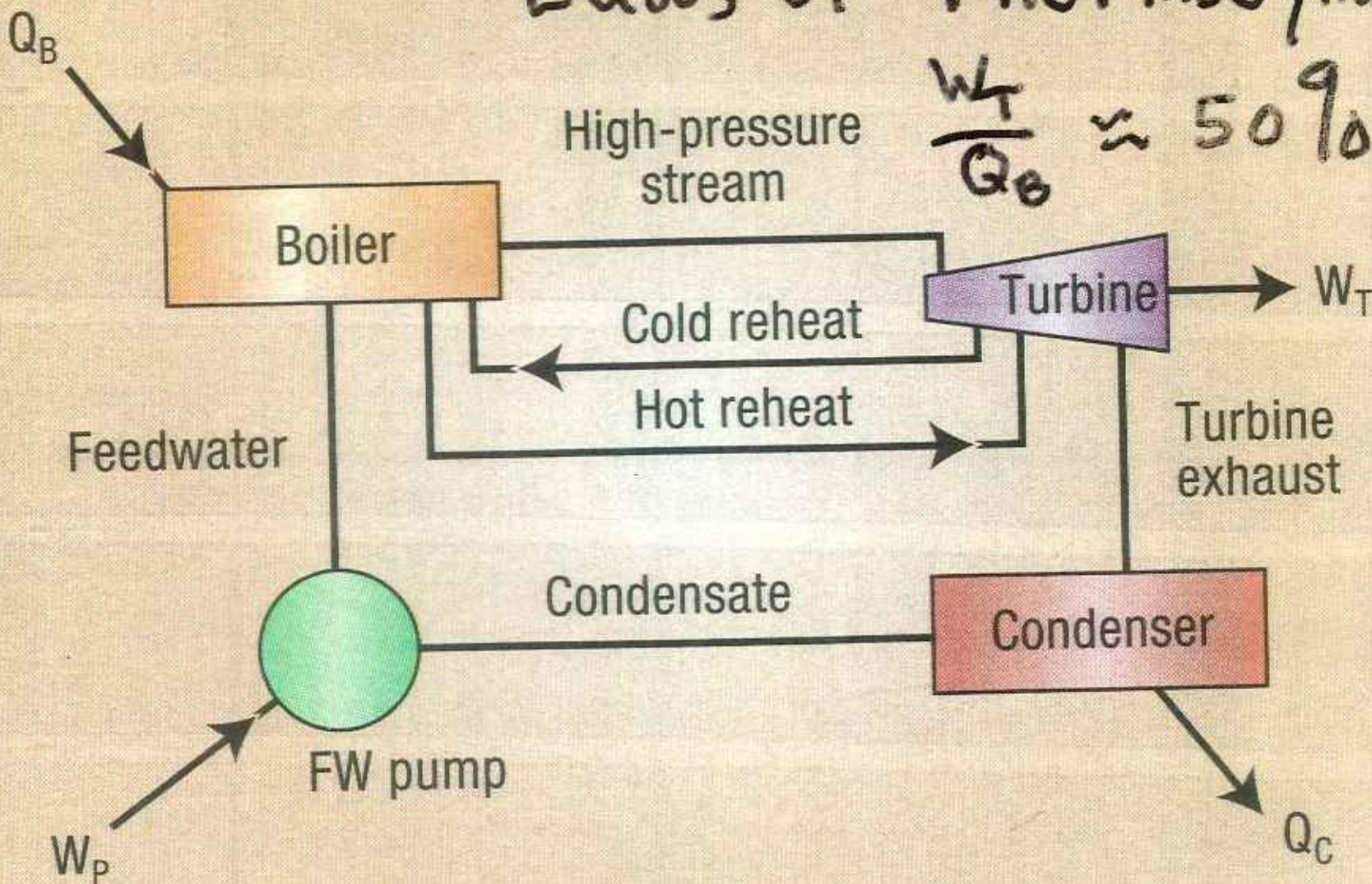
Generating stations

Technologies: Fossil Fueled

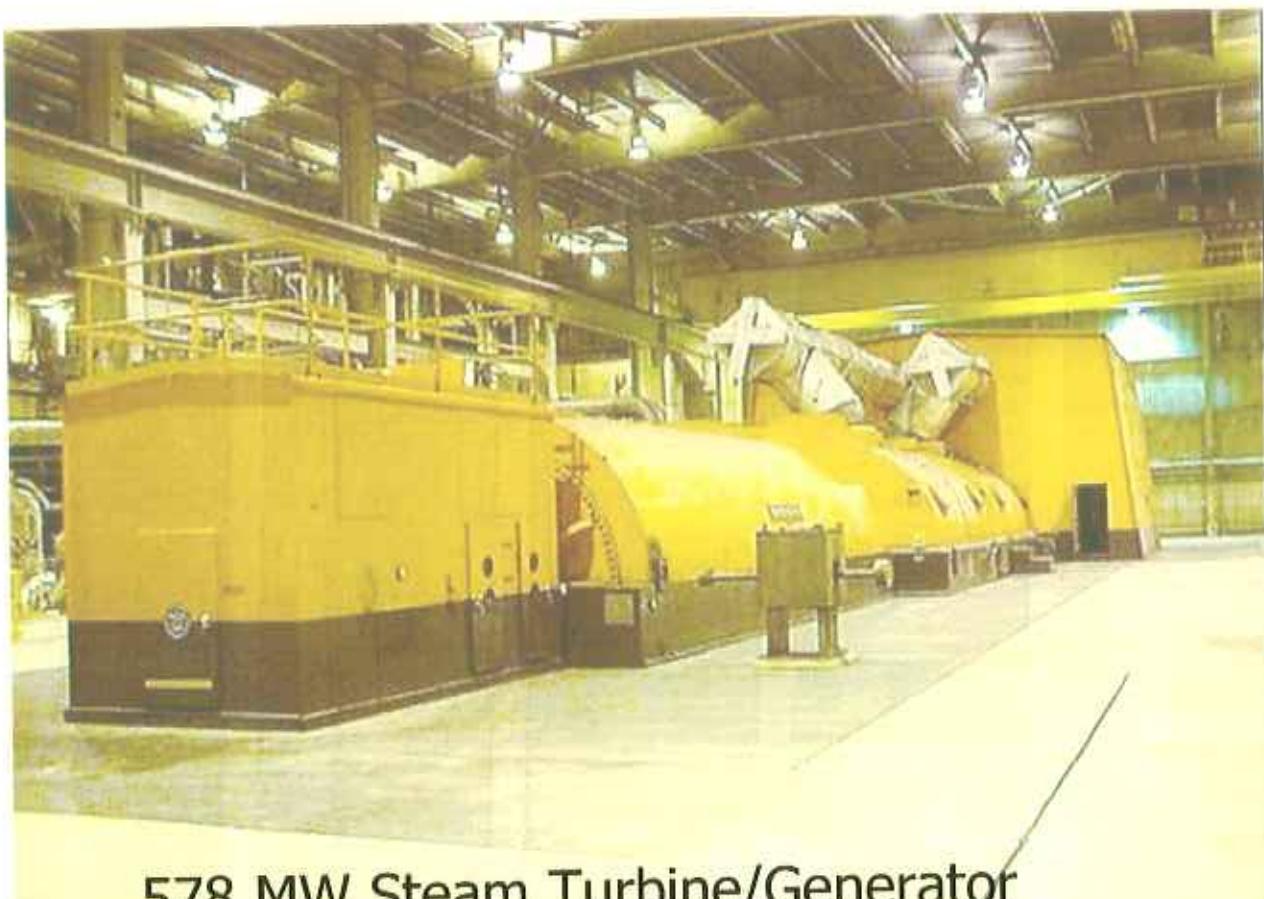
- **boiler/steam turbine**
 - coal
 - oil
 - gas
- **Combustion turbine**
 - gas
 - oil
 - coal gasification

Conventional Generation

Figure 2 STEAM GENERATOR WITH REHEATER



This is a practical illustr

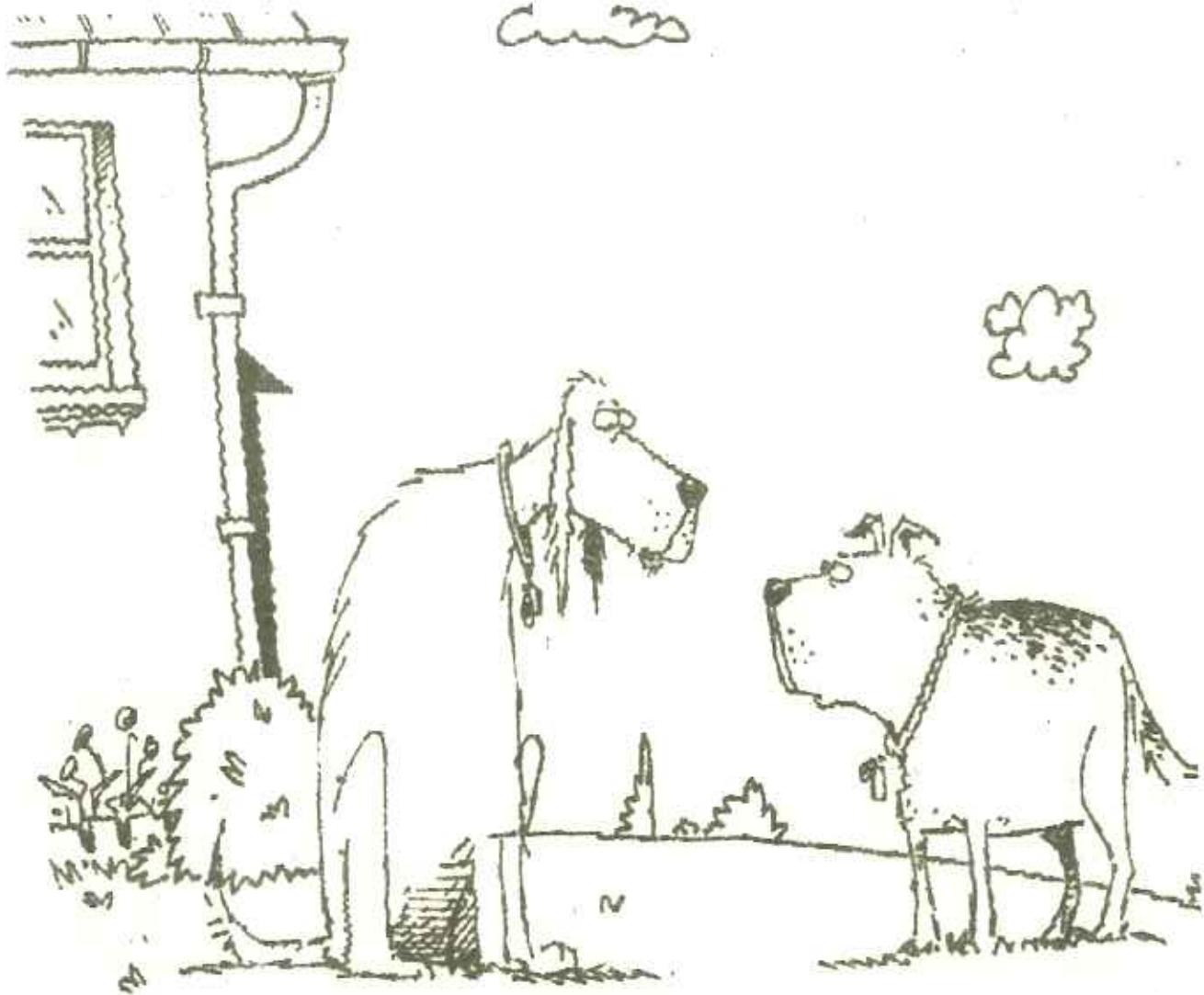


578 MW Steam Turbine/Generator

First Class in Power Engineering
Power Systems Landscape

February 11 - 13

20



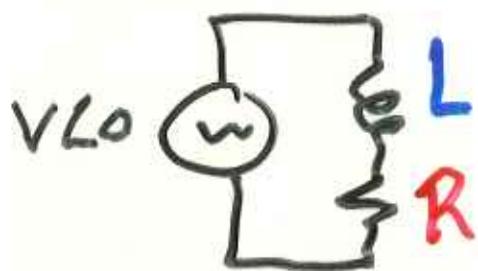
CADDWELL

*“Obedience school
prepared me
for everything but cats.”*

(Electric
Magnetic)

Circuits for
Power

Electric Circuits



$$\text{Phasors: } I = \frac{V_{L0}}{R+jX} \\ = I \angle -\Phi$$

S, P, Q, PF

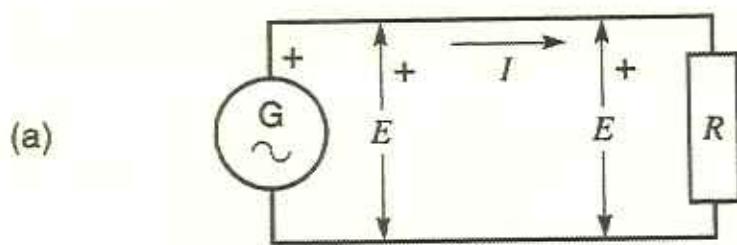


$$S = \sqrt{I^2} = \sqrt{P^2 + Q^2} \\ \text{VI cos}\phi \quad \text{VI sin}\phi$$

$$\text{PF} = \frac{P}{S}$$

$$0 \leq \text{PF} \leq 1$$

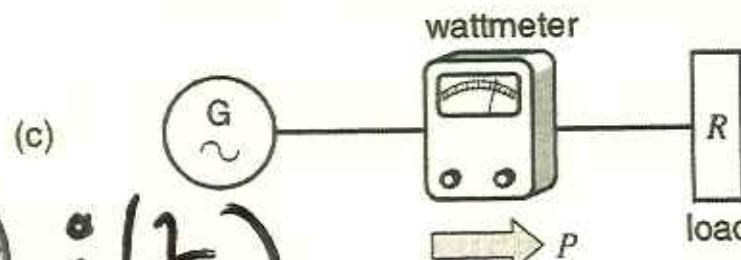
case for
max current
below
 I_{rated}



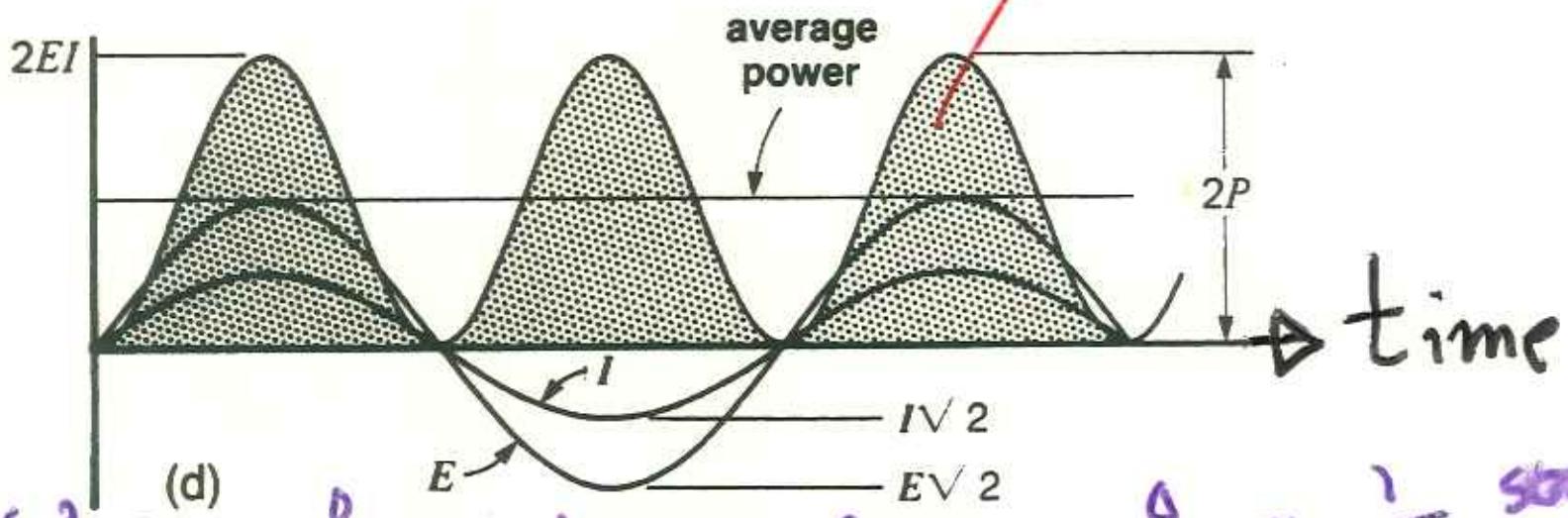
$$\theta \approx 0$$



$$S(t) \\ P(t) = v(t) i(t)$$



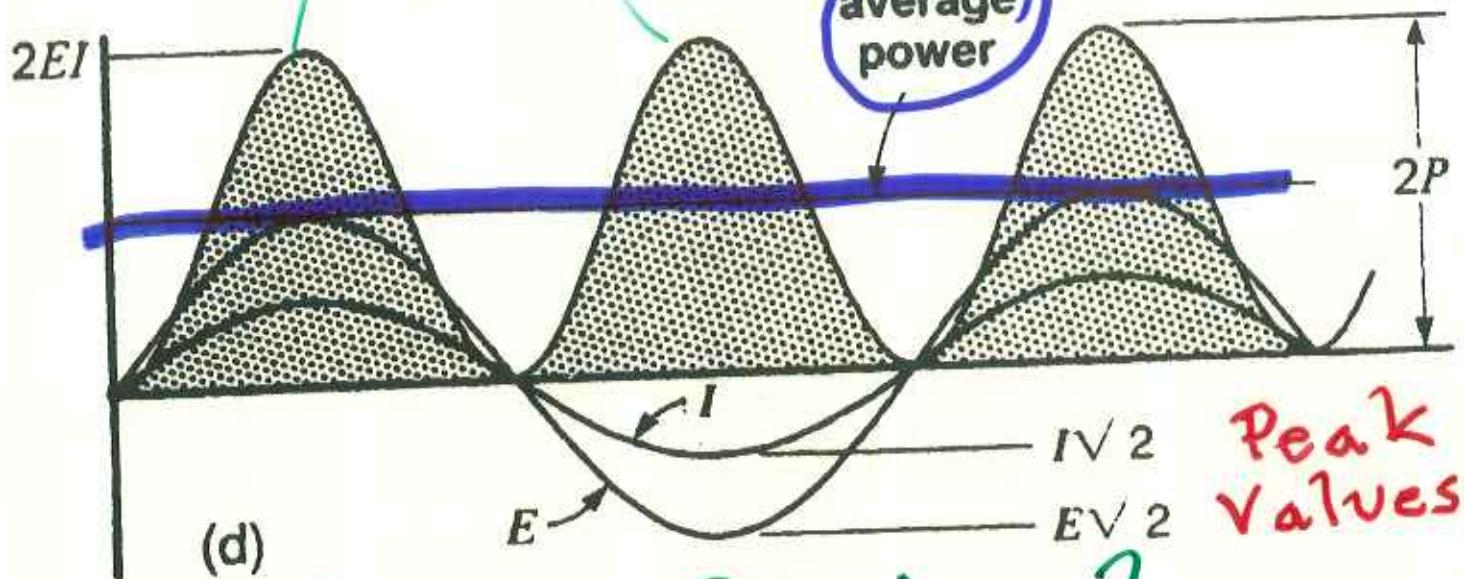
duration
of
pulse?



If $V \& I 90^\circ$ pulse width $\approx 90^\circ \approx \frac{1}{2470} \text{ sec}$

Power has [For I and E in phase]
 2 Peaks & both \neq P \Rightarrow $P_{AV} = \bar{I}_{RMS} \bar{E}_{RMS}$
 per cycle at load?
 What kind of what?

Fig 7.2
136



Why no -P pulses?
 $P(t)$ is a series of + pulses
 $P(t)$ always + implies?

E^2
 Unidirectional Power
 or active power
 units Watts

MOTOR TECHNOLOGY

10 High Torque Ripple

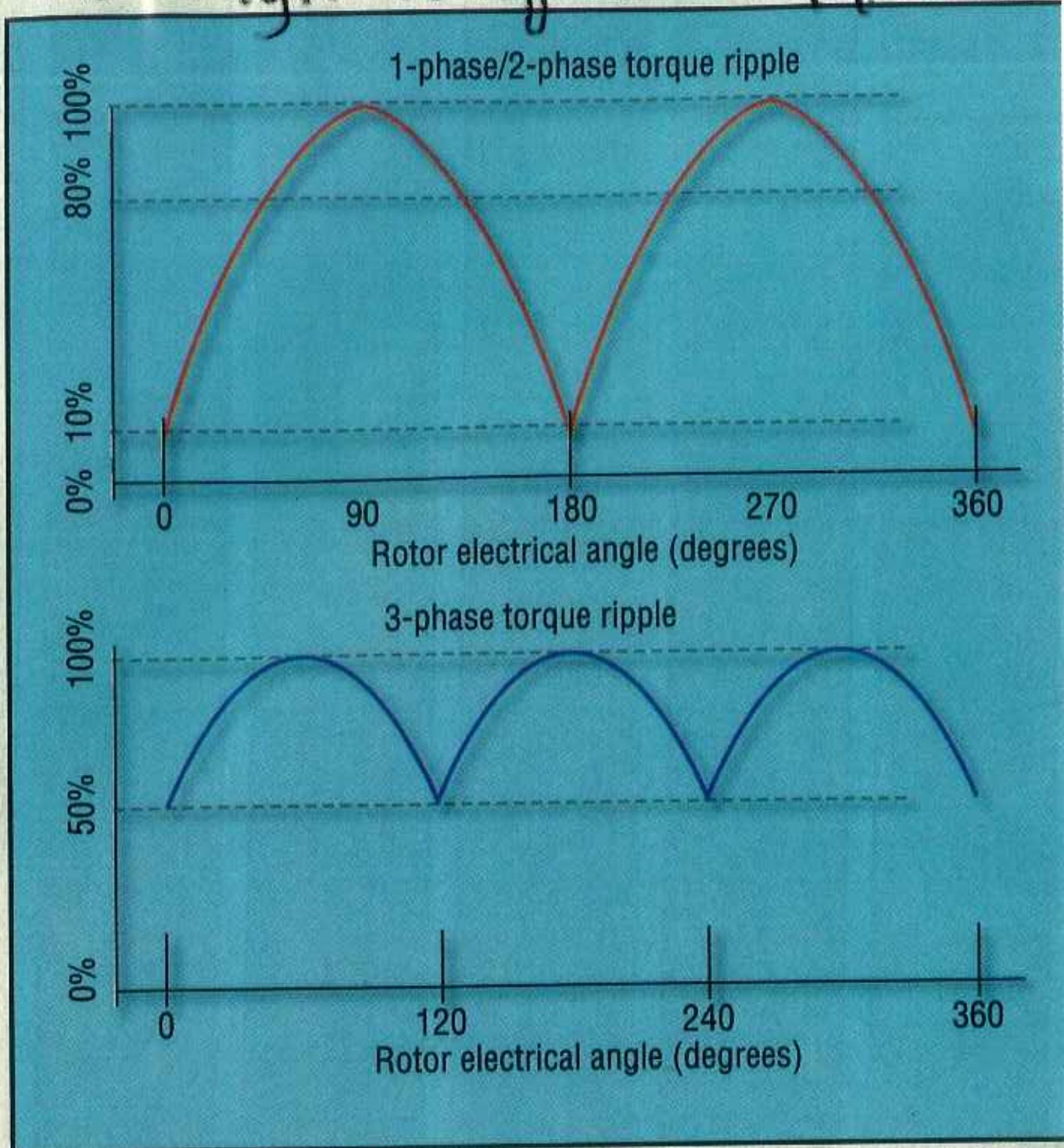


Fig. 7. A comparison of torque and rotation for 1-phase/2-phase fan motors versus 3-phase motors reveals that the former produce higher torque ripple, which results in more noise and poor starting torque.

Active (P) and Reactive (Q) POWER

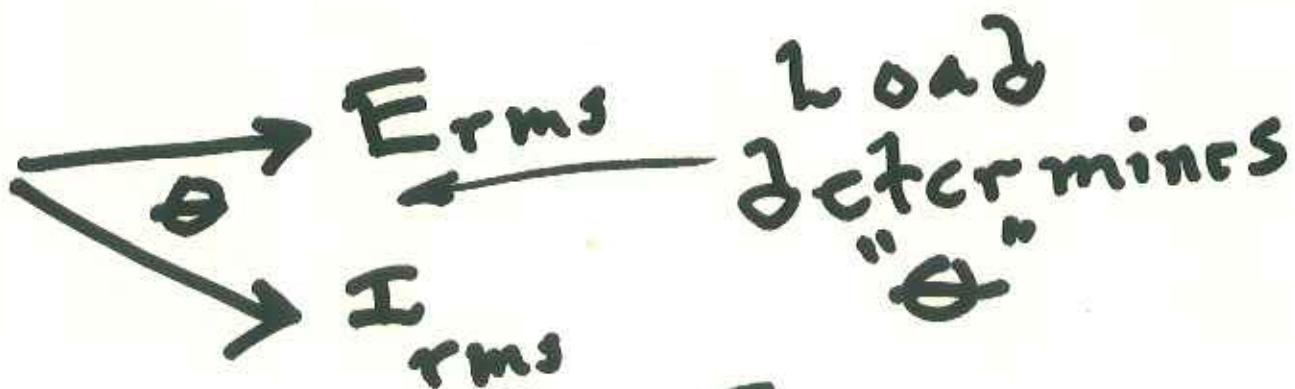
4

P Watts

Q VAR

E Phasor $\frac{E_{pk}}{\sqrt{2}} L^0 \angle \theta_f$

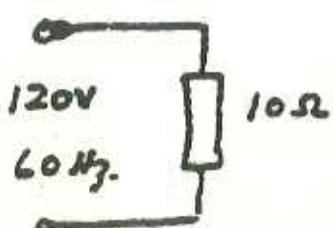
I Phasor $\frac{I_{pk}}{\sqrt{2}} L^{\pm} \theta$



$$\sqrt{2} E_{rms} \times ? = E_{peak}$$

Find P_A , S , P_{peak} , Δt (^{power}_{pulse})⁵

7-9



a. $P = \frac{E^2}{R} = \frac{120^2}{10} = 1440 \text{ W}$ ← note

b. $S = EI = 120 \times 12 = 1440 \text{ VA}$

c. Peak power = $120\sqrt{2} \times 12\sqrt{2} = 2880 \text{ W}$

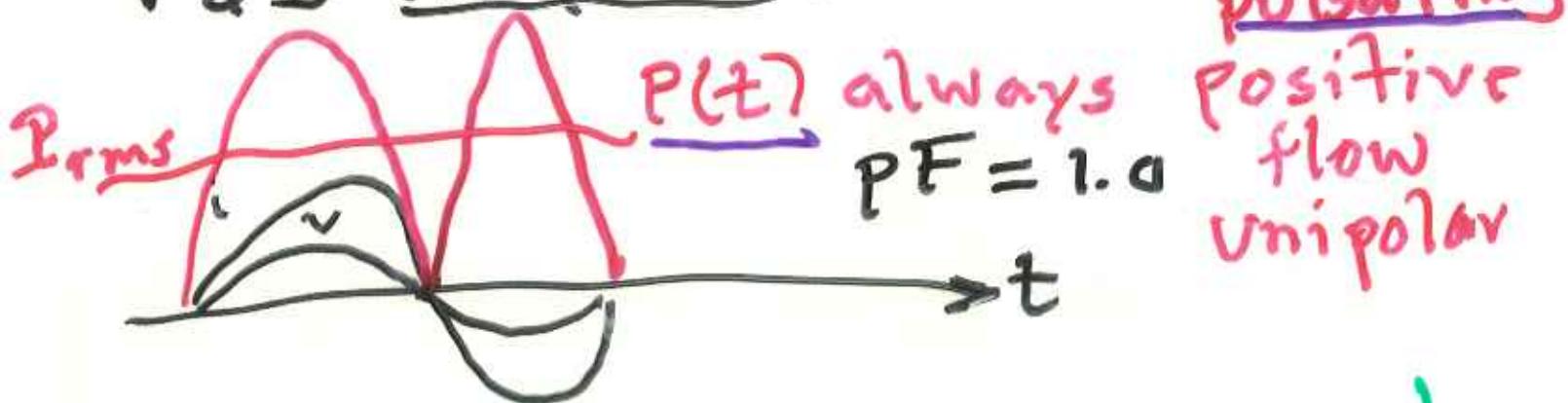
d. each pulse lasts for $1/120 \approx 180^\circ$ 2.7

(Note that apparent power S is always expressed in volt-amperes even though we know that only active power (watts) are being consumed).

$Q = ?$

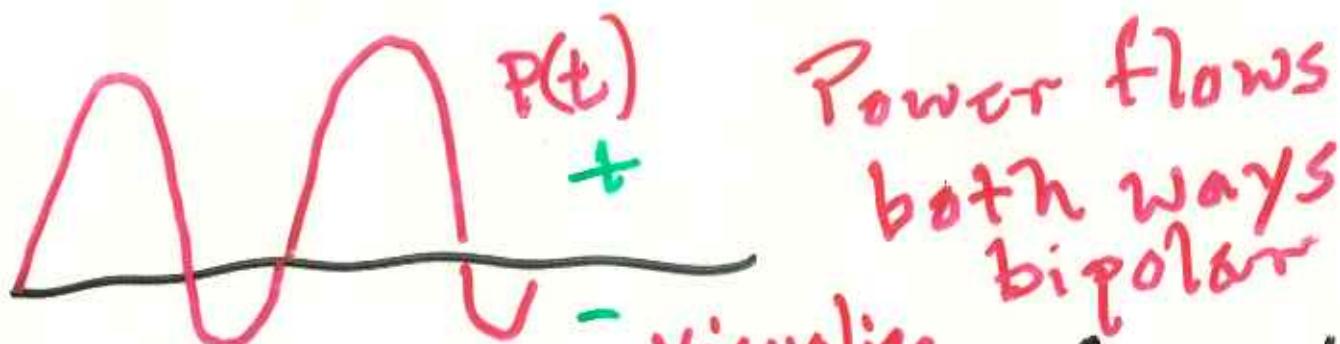
Q_{min}^0
for
smallest

V & I in phase

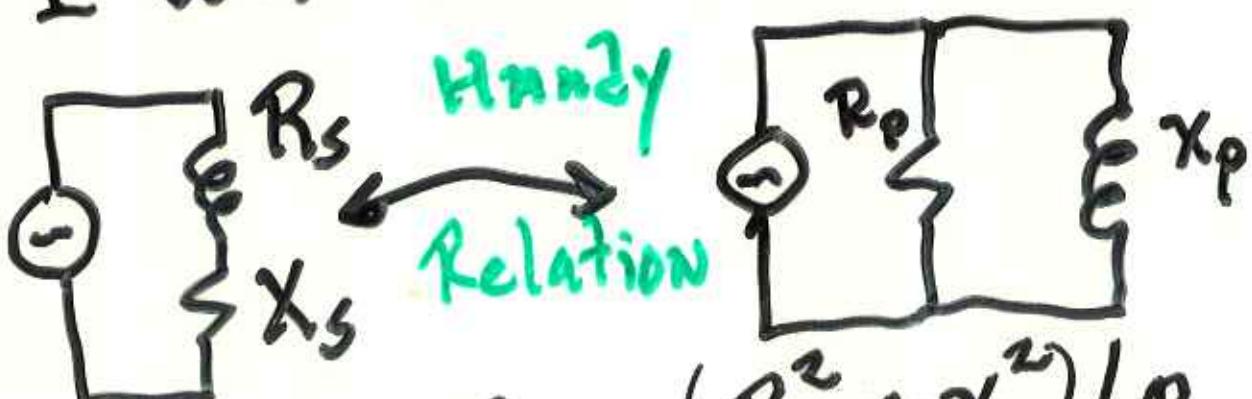


V & I out of phase

Whoa!

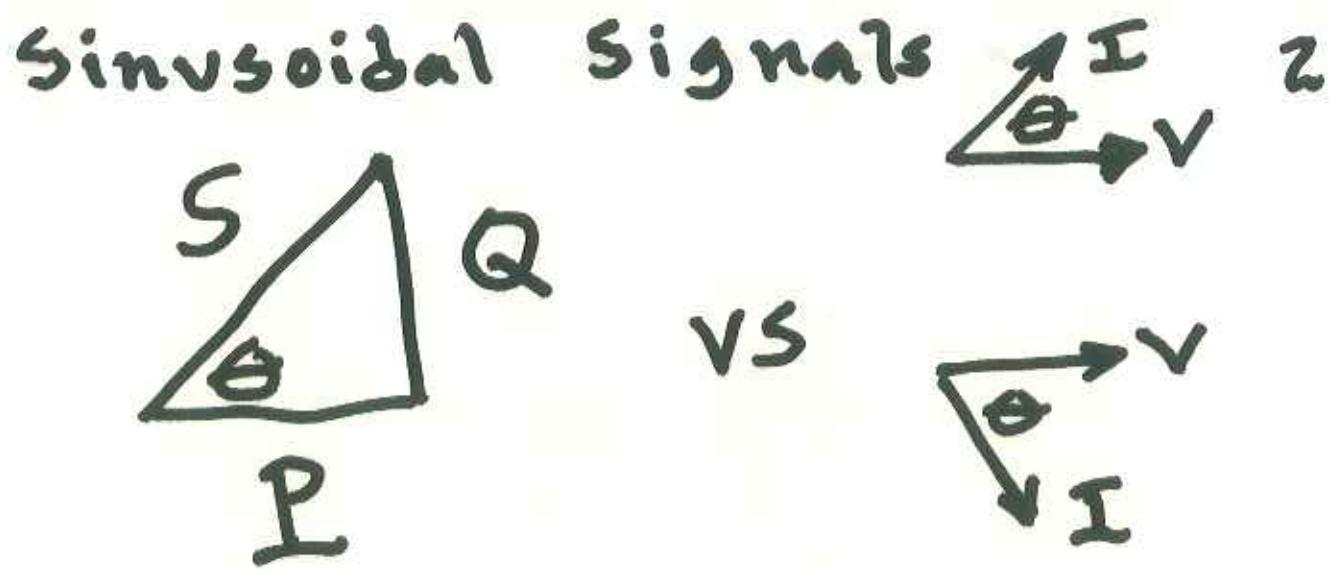


How to best grasp where is P where is Q



$$\text{exam } R_p = \frac{(R_s^2 + X_s^2)}{R_s}$$

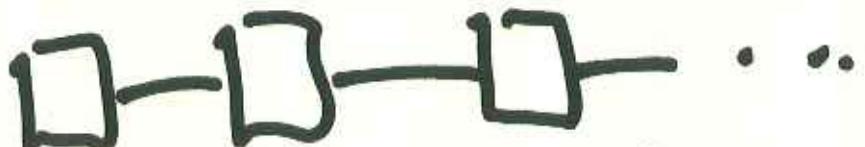
$$\text{exam } X_p = \frac{(R_s^2 + X_s^2)}{X_s} ?$$



Is P always + ?

Is Q bipolar ?

what flows the same
in all blocks ?



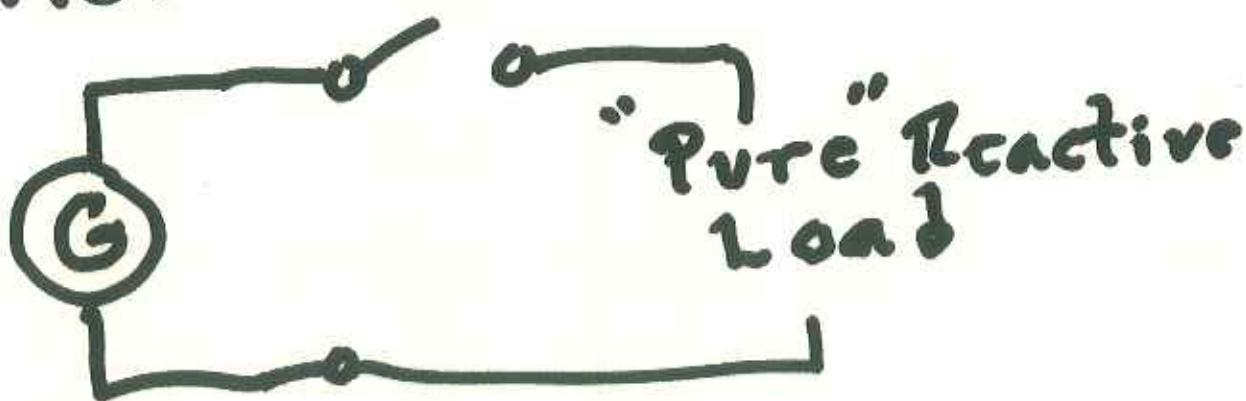
Power System

Is S Constant ?

SPQR ? Does power flow
through wires?

Reactive Power

6



E_{L0}

I_L ?

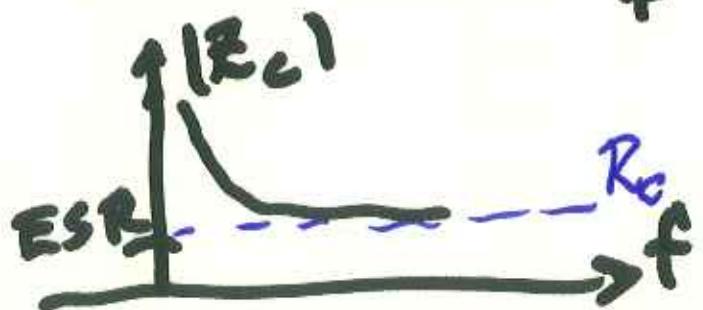
Reactances

ESR



for "L" load

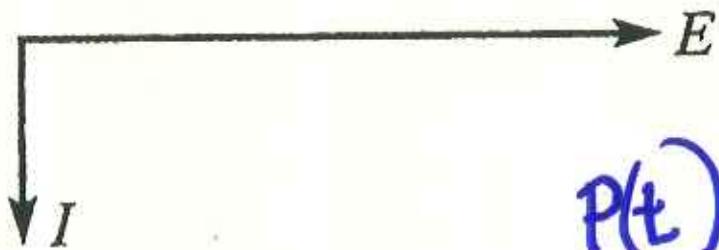
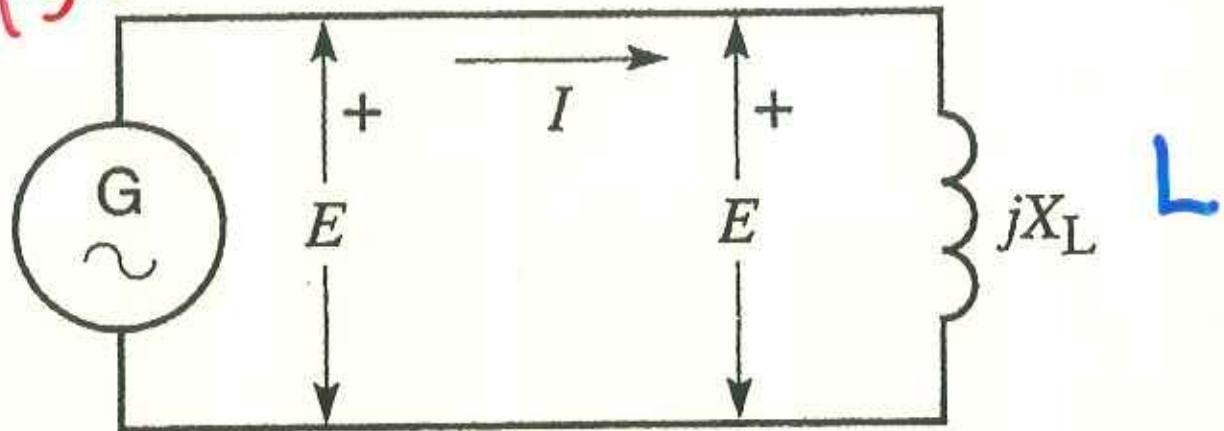
for "C" load



? ESR varies with f AC?

Pure \times
No power flow
All Q flow

Fig. 4
13x



$$|I| = ?$$

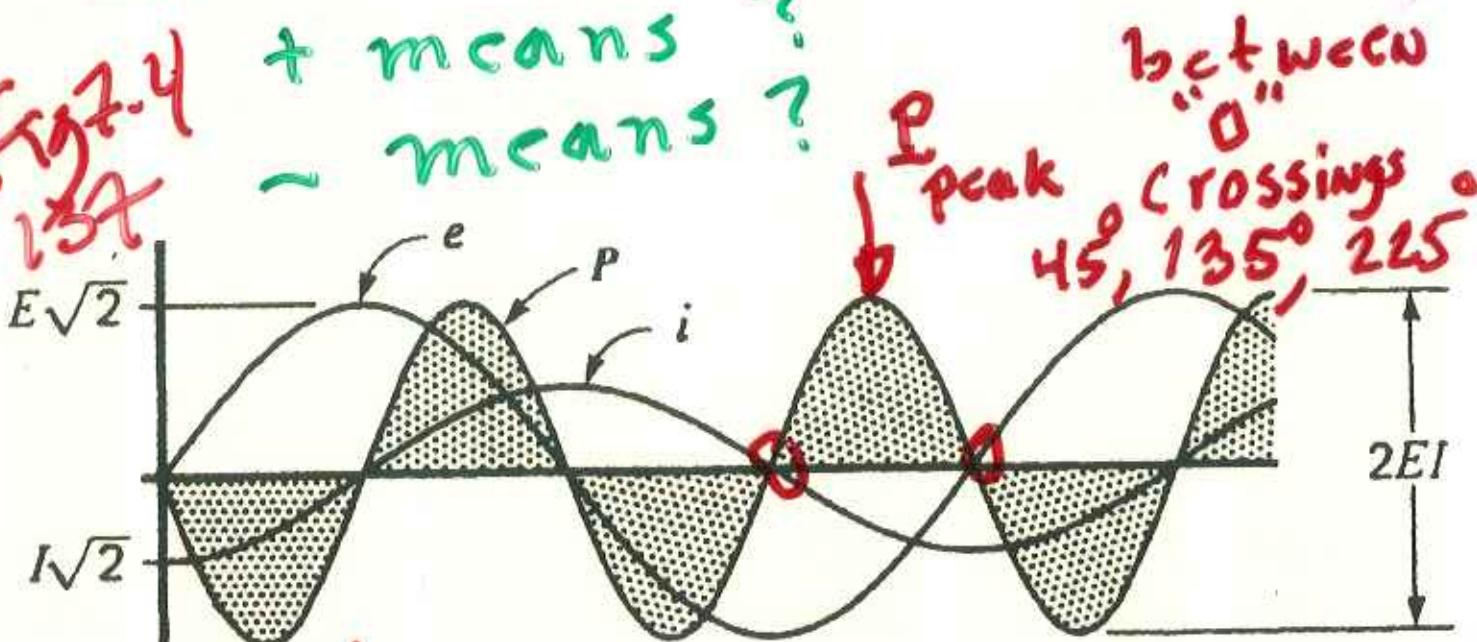
$$\begin{aligned} P(t) &= \text{all } + ? \\ - &= \text{all } - ? \end{aligned}$$

$$LI = ?$$

$$E_{\text{peak}} = E_{\text{rms}} + ?$$

5b
P(t) has bipolar properties

~~first 1/2~~ + means?
~~last 1/2~~ - means?



Power wave duration
 $\frac{1}{4}$ cycle of
 mains cycle

f of P
is

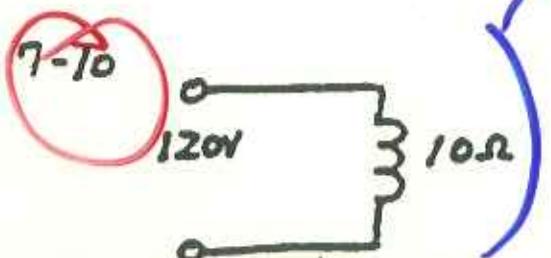
? * mains f

$$\text{or } \frac{1}{(4)60} = \Delta t \approx 4.15 \text{ ms pulses}$$

or 90° of phase
 Bipolar power flow vs time
 has units VARS

VAR Meters are available
 at 60 Hz (why not 600 Hz?)

Calculate: Q , S , $P_{\text{peak out}}$ & at of power pulse



a. $Q = \frac{E^2}{X_L} = \frac{120^2}{10} = 1440 \text{ var}$

b. $S = EI = 120 \times 12 = 1440 \text{ VA}$

c. Referring to Fig 7-7c, the peak power

occurs exactly between the zero-power
 $\Delta t = \frac{1}{2} \{\Delta t_{\text{power}}\} = \frac{1}{2} \left[\frac{1}{4(60)} \right]$

7-10 crossing points. Peak power occurs \therefore at 45° , 135° , 225° , etc. At these instants (45° say)

$E = 120\sqrt{2} \sin 45^\circ = 120V$

300
600

$i = 12\sqrt{2} \sin(45 - 90) = -12A$

Key \therefore peak power = $1440 W$ (not var, not VA)

d. 1440W reactor gives back

e. each pulse lasts for 90° or $1/240 \text{ s}$.

$90^\circ = \frac{1}{4} \text{ cycle mains}$

$P_{Ar} = ?$

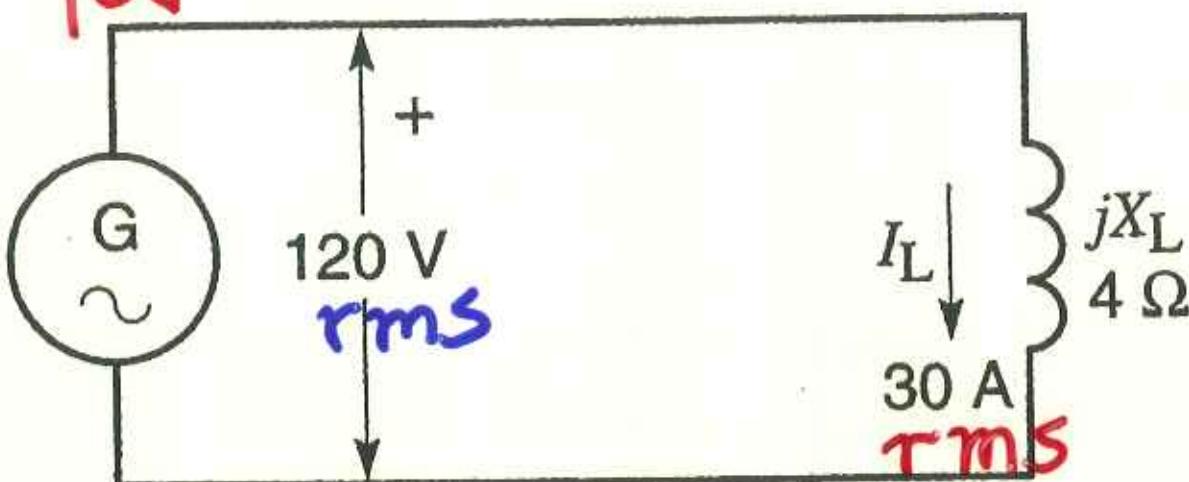
$\frac{1}{4} (16.66ms)$

Not 2880
Why

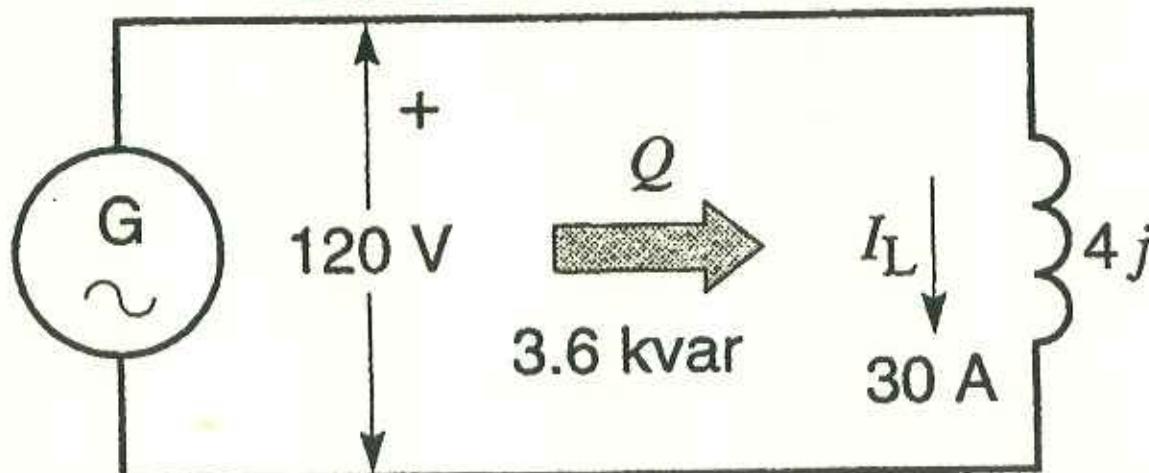
6a

load that absorbs "Q"
reactive power is "L"

Fig 7.6
138



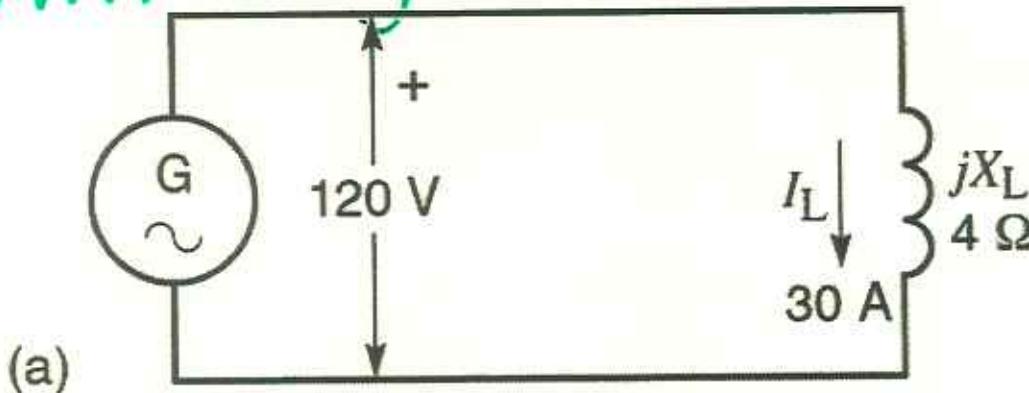
$$Q = EI \sin 90^\circ$$



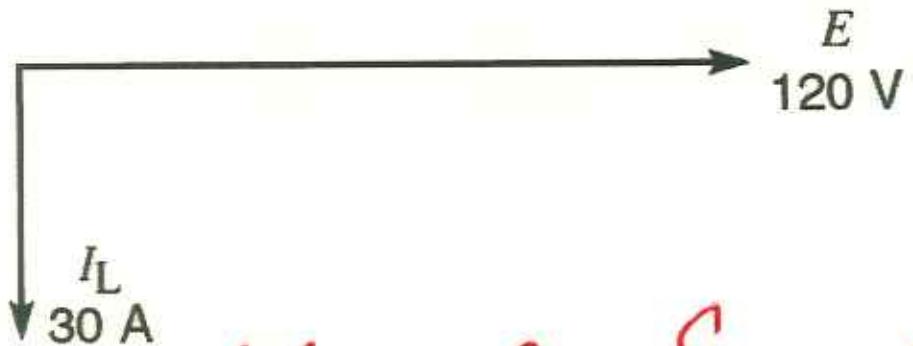
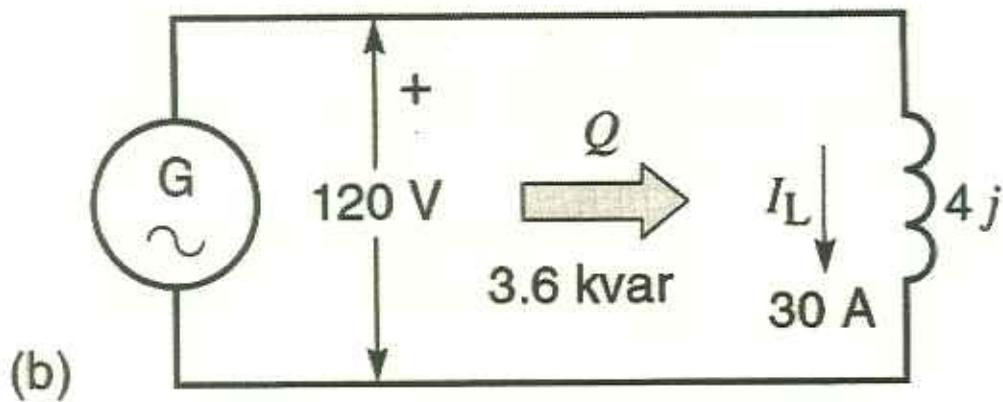
supplies
Q

absorbs
Q

Summary Q₂



G sources
 L sinks



How Different for C (load)

Load that provides reactive power is "C"

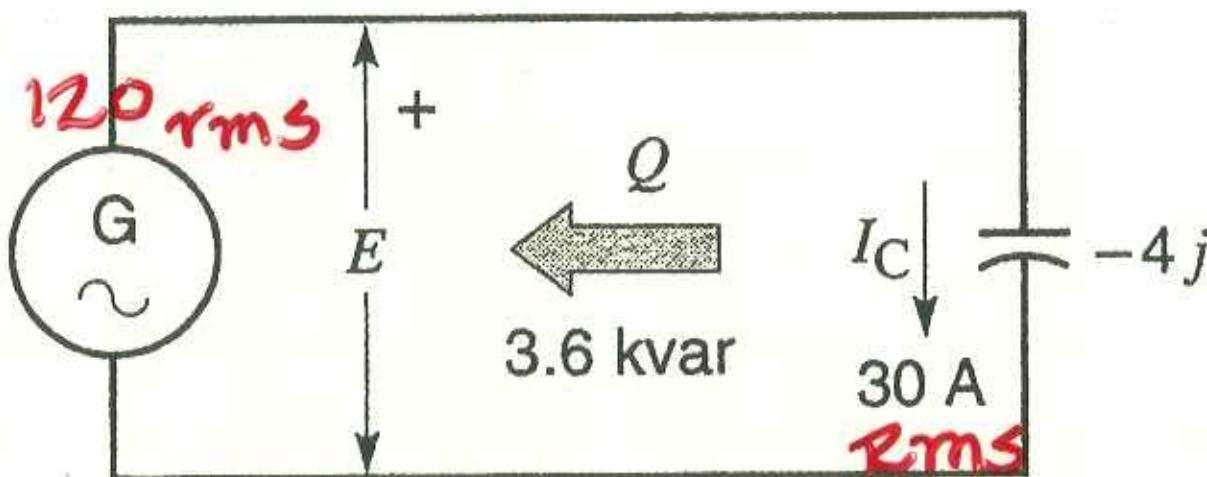
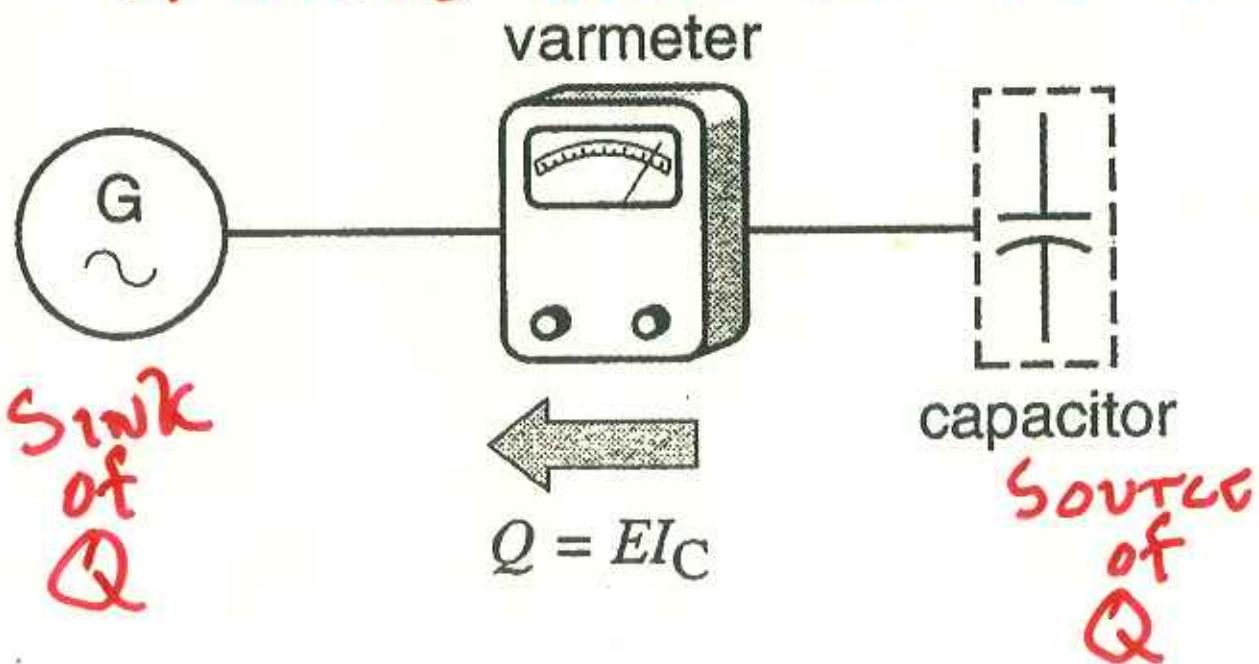
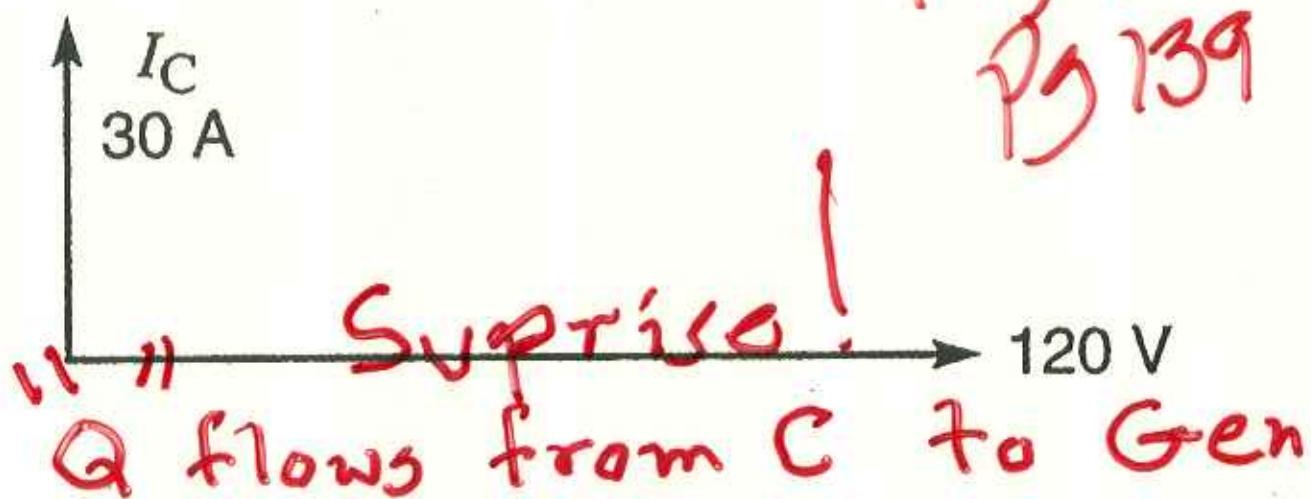
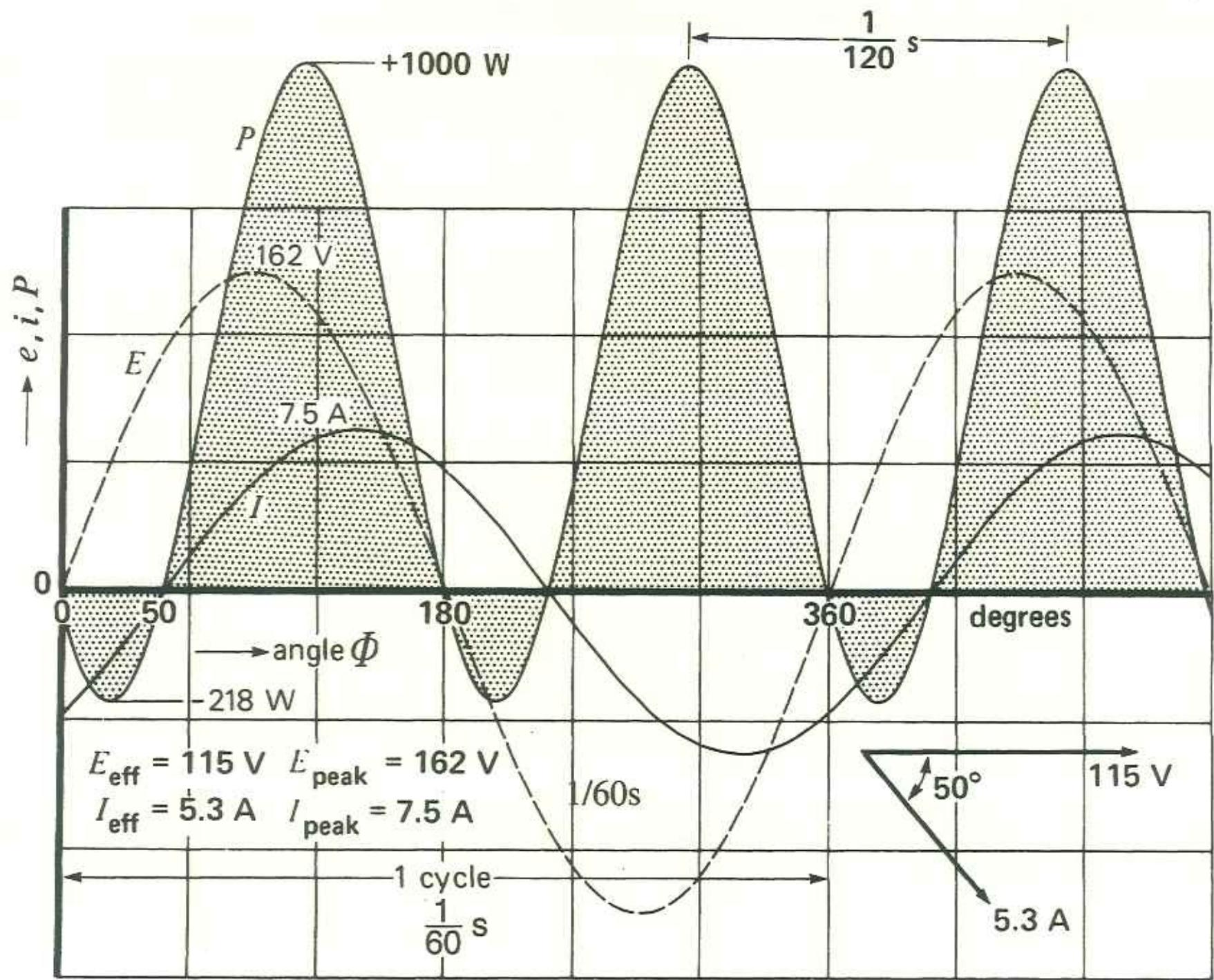
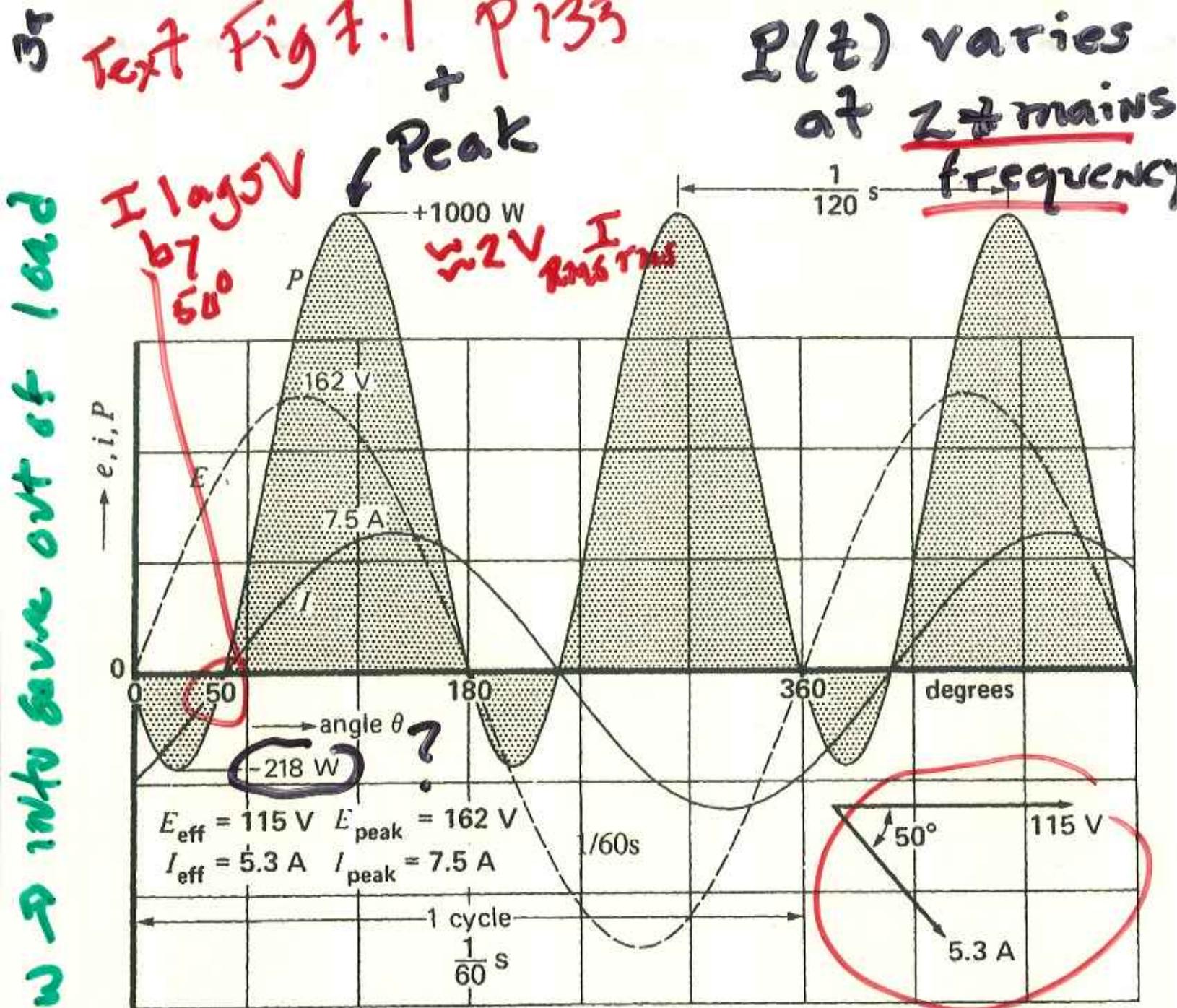


Fig 7.8
Pg 139



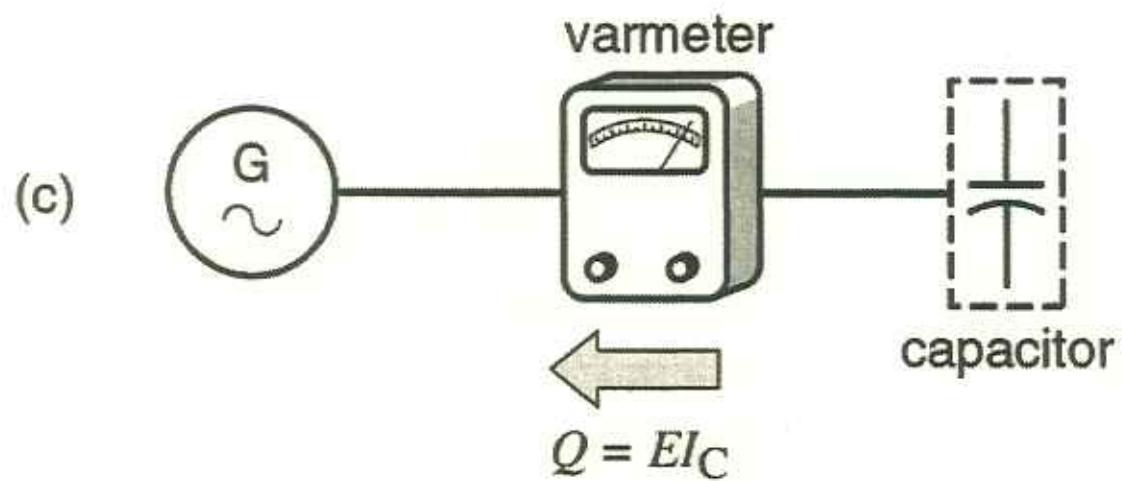
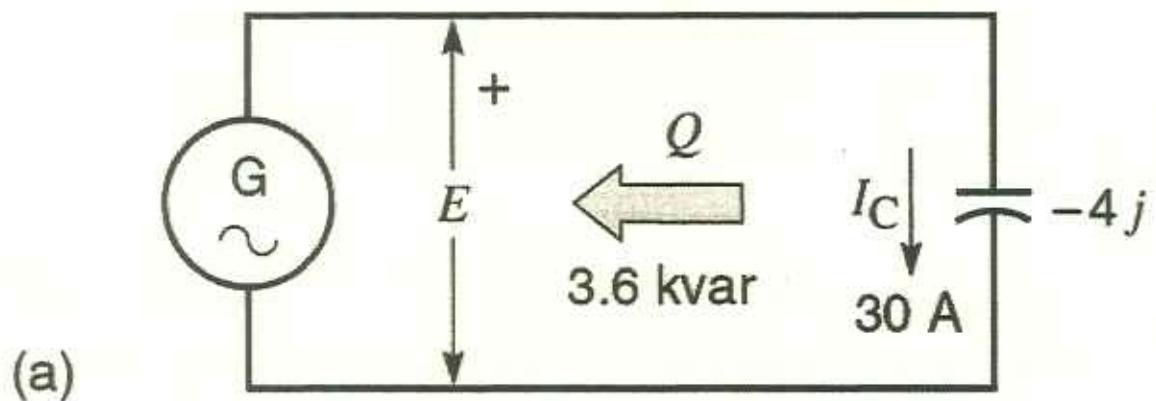


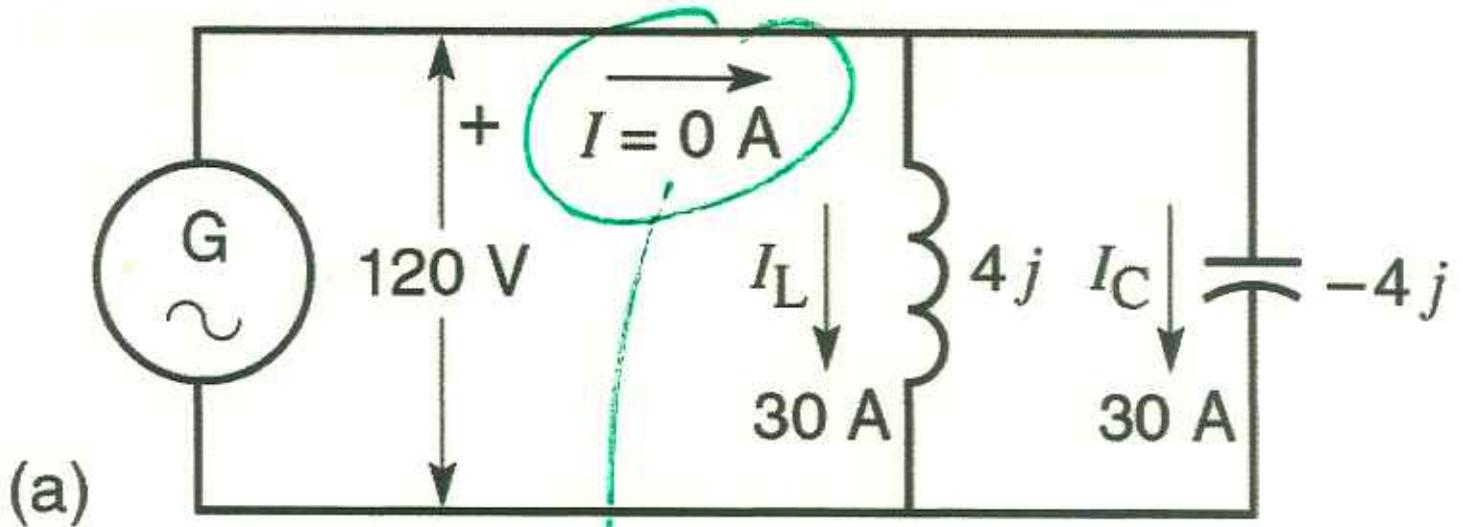


Negative Power means?

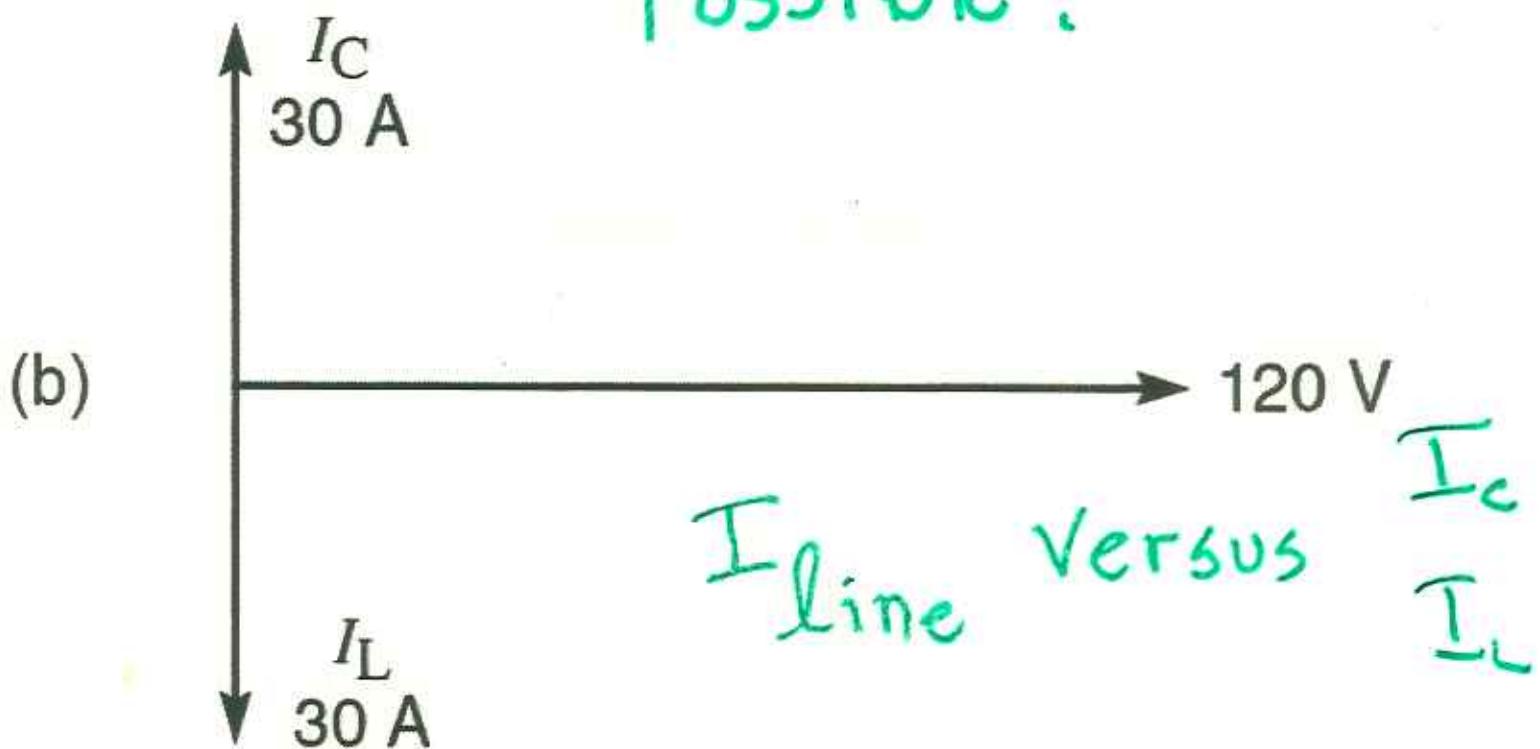


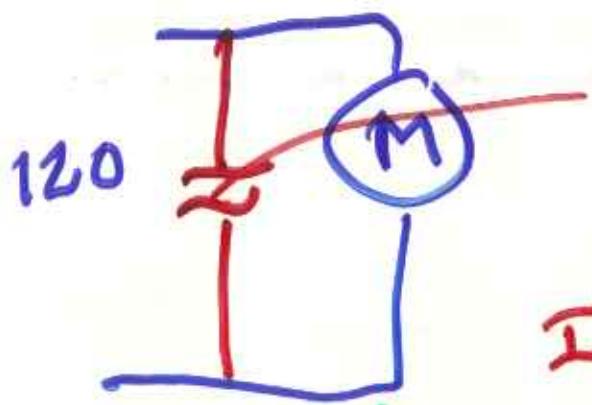
$+P(\text{peak})$ vs $-P(\text{peak})$ over varies with & simplified





Possible?



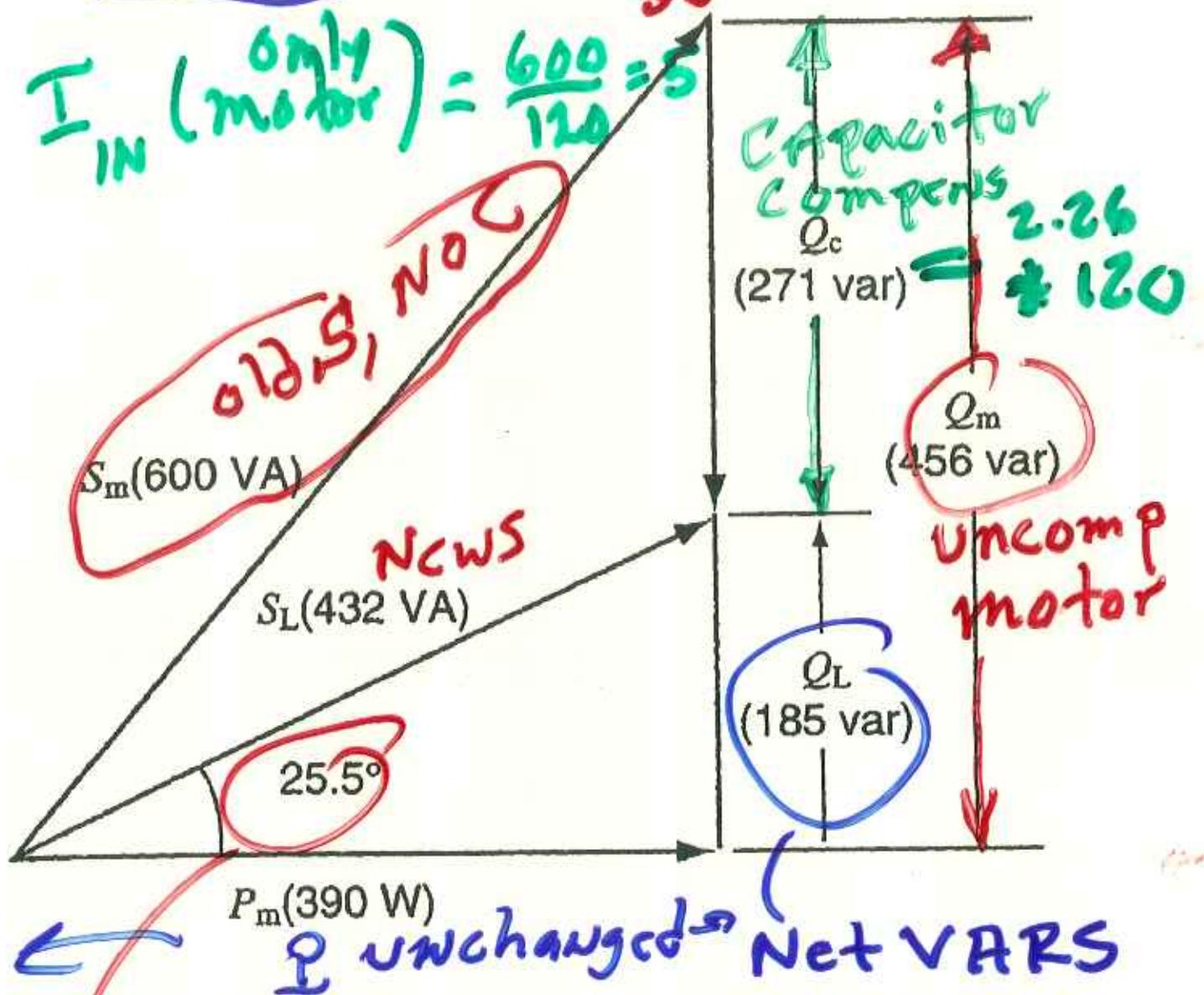
15
a

Add $50 \mu\text{F}$

$$X_C = \frac{1}{2\pi f C} = 53 \Omega$$

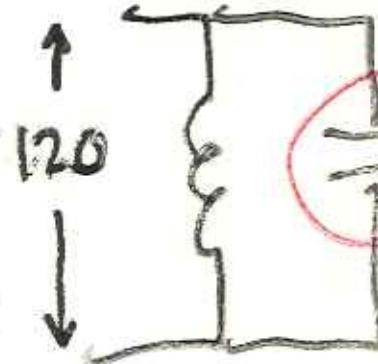
$$I_C = \frac{120}{53} = 2.26 \text{ A}$$

I_{IN} (motor) = $\frac{600}{120} = 5$

New θ

PF now $\cos^{-1} \frac{P}{S} = \cos^{-1} \frac{390}{432} = .9$

New $I_{IN} = \frac{S_{new}}{E} = \frac{432}{120} = 3.6$ Good?



$$I_{IN} = \frac{600}{120} = 5A$$

add C to
reduce I_{IN}
via Q_C

Reduce
 I_{IN} (motor
plus C)

$$= \frac{432}{120}$$

$S_L(432 \text{ VA})$

25.5°

$P_m(390 \text{ W})$

C sources Q reduces $(\frac{I_{IN}}{Q})$ from mains

Q_C
(271 var)

NOC
 Q_m
(456 var)

Q_L
(185 var)

} with
C

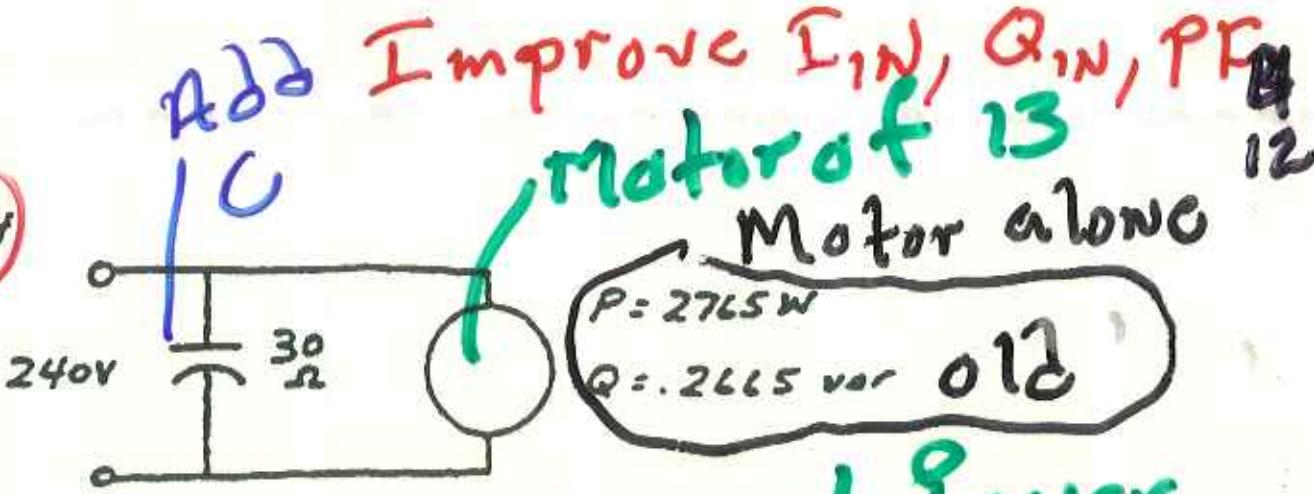
measure
Q
original
motor

$$S_m = 600$$

$$V_{IN} = 120$$

$$I_{IN} = 5A$$

7-14



a. 2765 W

b. $Q_L = 240^2 / 30 = 1920 \text{ var}$

c. $Q_L = (2665 - 1920) = 745 \text{ var}$

d. $S = \sqrt{2765^2 + 745^2} = 2864 \text{ VA}$

e. $\cos \theta = P/S = 2765/2864 = 0.965 = 96.5\%$.

Now total

Q

New S

$$Q_C = \frac{V_C^2}{X_C}$$

Same motor power

Use external C

improve $Q_{IN} \downarrow I_{IN} \downarrow$
 $\text{PF} \uparrow$



There's nothing better than finding \$20 in your pocket.

Unless, of course,
it's finding \$2,000,000 hidden in your plant.

Electric Utility Industry Organization

Federal Energy Regulatory Commission (FERC)

- Federal Agency**
- Jurisdiction over all interstate energy commerce**
 - regulate transmission system use**
 - creator of standard market design**

Electric Utility Industry Organization

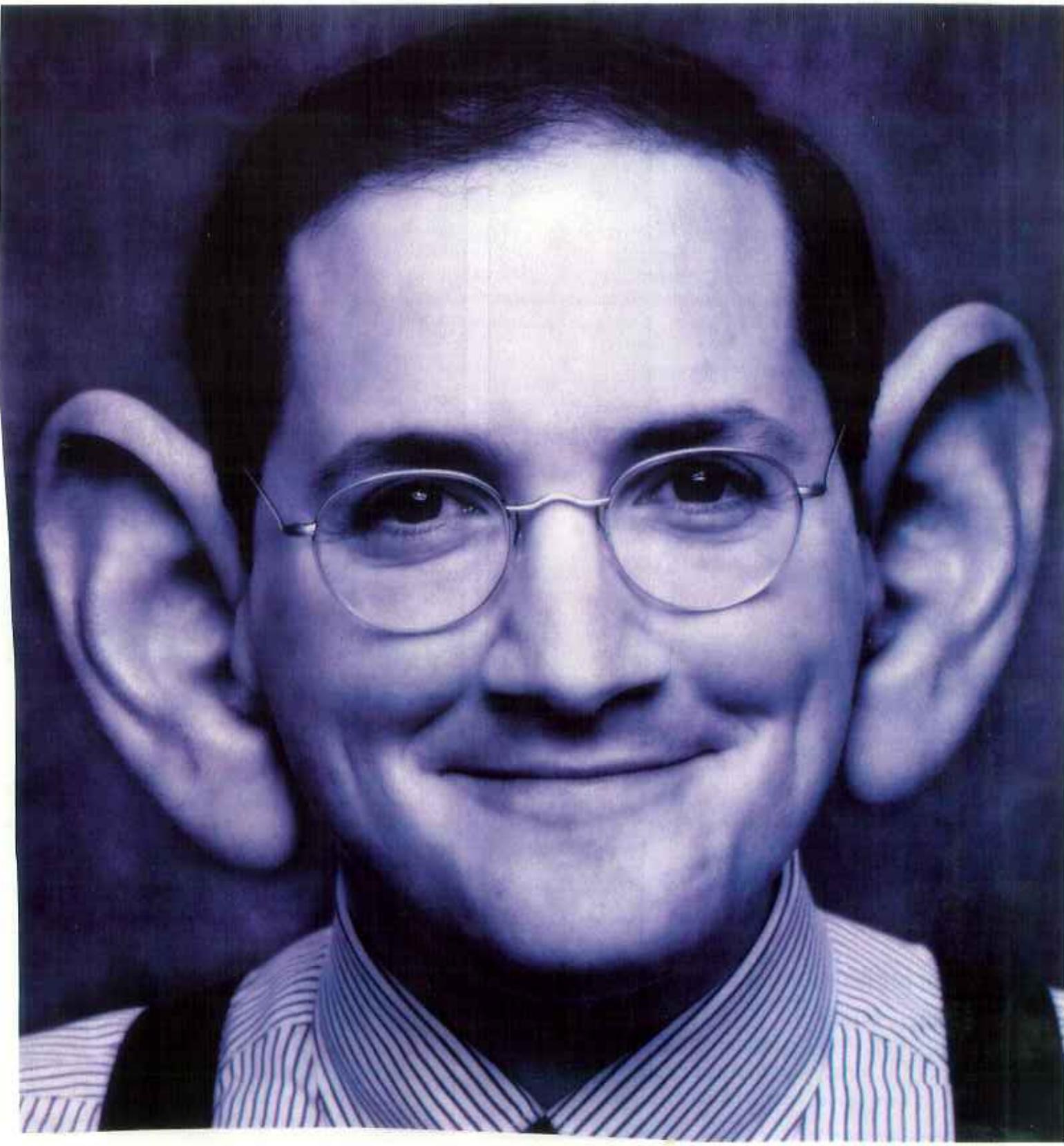
Public Utility Commissions (PUC)

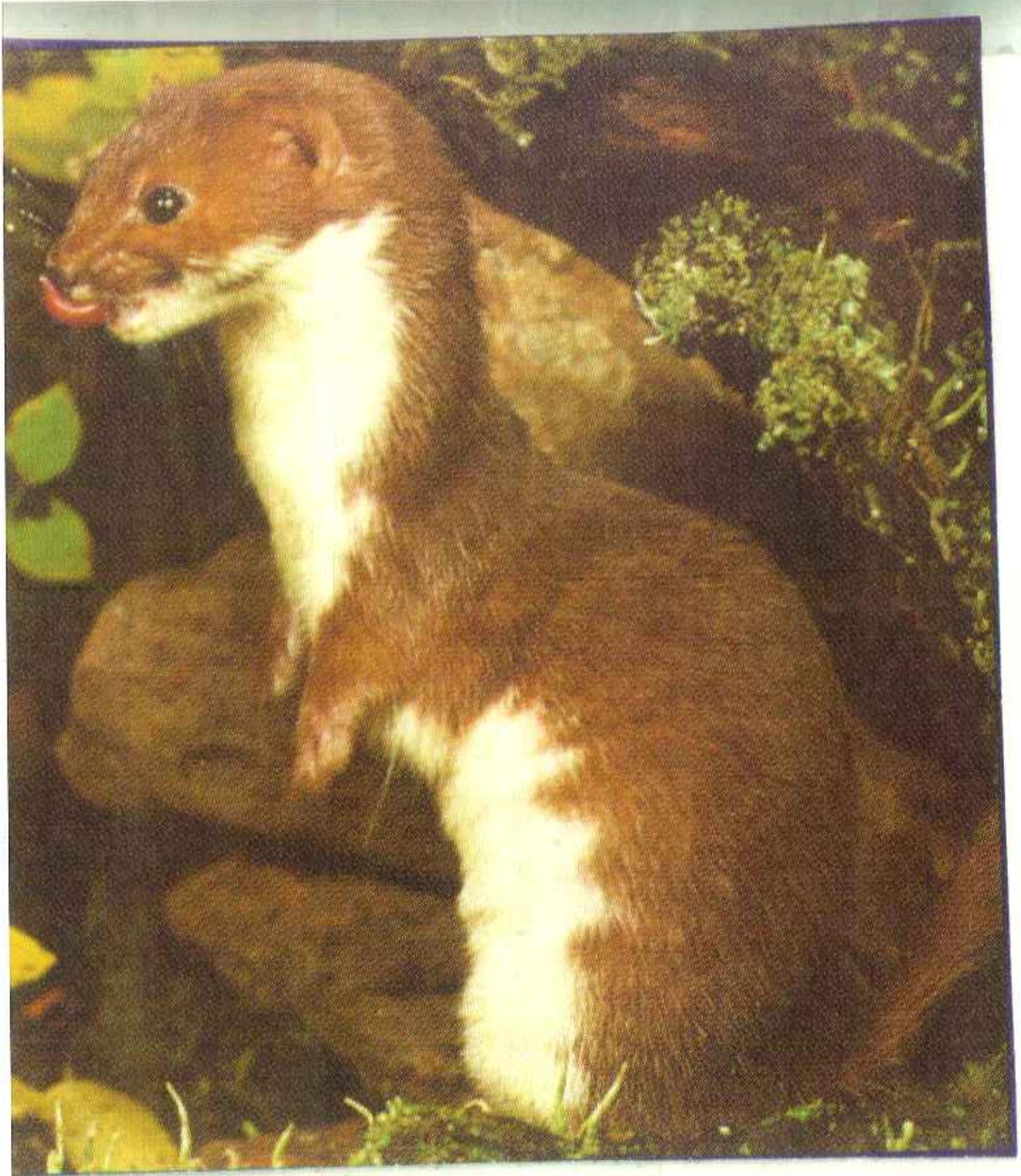
- State Agencies**
- Jurisdiction over retail sales**
 - public power and cooperatives exempt**
 - regulate distribution system use**
 - approve retail rates**
 - establish retail programs (conservation, new tech, etc)**

Electric Utility Industry Organization

North American Electric Reliability Council (NERC)

- Industry Organization**
 - voluntary**
 - compliance through public and peer pressure**
- Reliability Based**
 - formed after 1965 blackout**
 - organized into reliability regions**





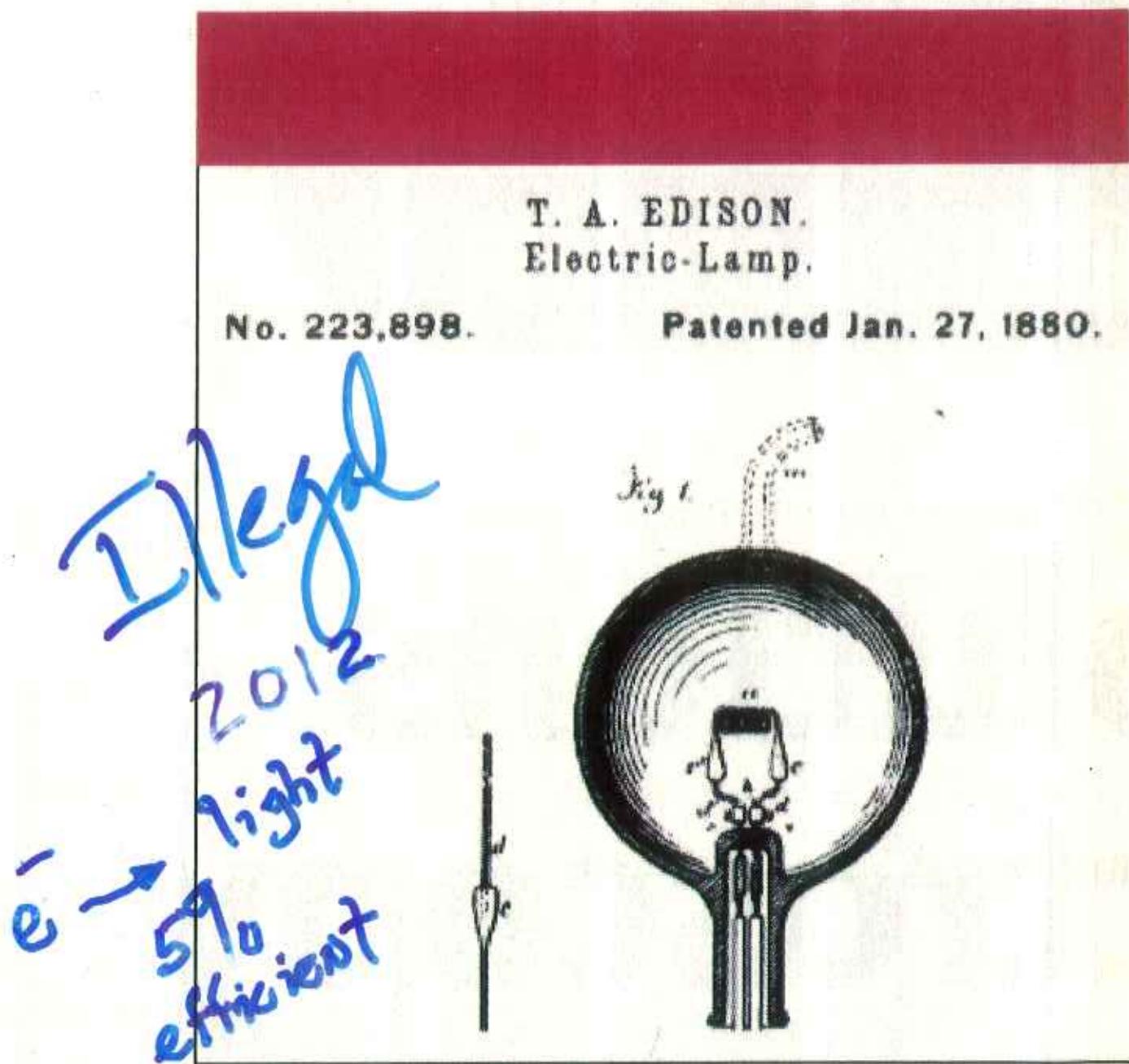


Figure 1: Image of Thomas Edison's electric incandescent lamp that was part of his original patent application (reprinted from reference 1).

Generating stations

Classifications per *IEEE 1547-2002*

- **Distributed generation stations**
 - not directly connected to the transmission system
 - less than 10 MW aggregate capacity
- **Central generation stations**
 - everything else

Generating stations

Classifications per FERC 18 CFR Part 35

- Large generators (Part II – final rule)**
 - greater than 20 MW (aggregate?) capacity**
- Small generators (Part III – NOPR)**
 - less than 20 MW (aggregate?) capacity**

Conservation vs economics

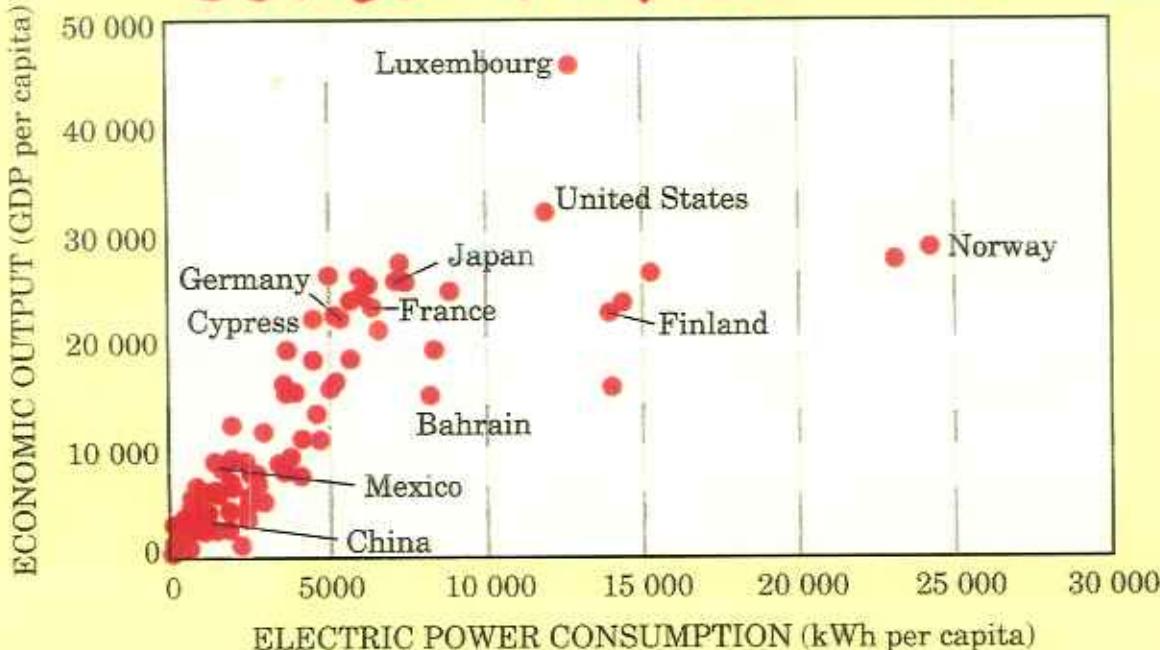


Figure 2. Economic output, as measured by the gross domestic product (GDP) per capita, is strongly correlated to the use of electricity. Nations in which the annual demand for electricity exceeds 10 000 kilowatt hours per capita have either emerging or developed economies. The GDP is expressed in terms of the so-called purchase power parity, a standard economic measure used for international comparisons. (Data are from *World Development Indicators*, World Bank, 2004.)

Conservation Works

Germany
Japan
"Nega" Watts

Energy
use

\approx GDP



Overcharged

Factories outside the U.S. are often more willing to invest in energy efficiency because they usually pay more for electricity than their American counterparts. Electricity prices for industry, in U.S. cents per kilowatt-hour, first quarter 2007.

COUNTRY	U.S. CENTS PER KILOWATT-HOUR
Italy	23.6
Ireland	15
U.K. ¹	13.2
Hungary	12.8
Slovak Republic	12.8
Austria	12.6
Portugal	12.3
Japan ²	12
Czech Republic	10.8
Mexico	10.3
Turkey	10.1
Spain ³	9.1
Germany ²	8.4
Switzerland	8.2
Finland	8
Poland	7.8
South Korea	6.8
Greece ²	6.7
New Zealand	6.6
U.S. ⁴	6.1
Norway ¹	5.7
France	5.3

cheap coal

cheap hydro

cheap nuclear

¹ 4th quarter 2006

² 2005

³ 2006

⁴ Price excluding tax

Source: International Energy Agency



ONE HOT ROCK



But SO_x NO_x Hg & Ur

Cost energy vs Pollution

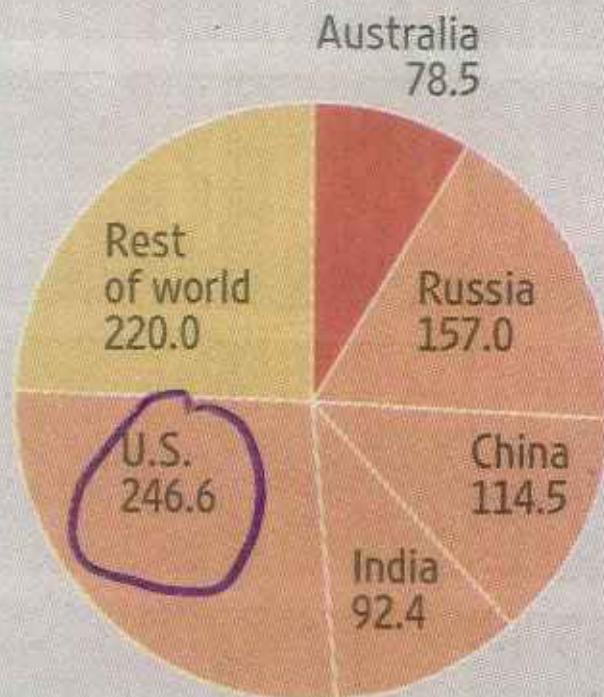
More Coal, at a Cost

Australia got 45% of its energy from coal in the year ended June 2004, but coal was the source of 54.8% of its greenhouse-gas emissions from energy, which are thought to contribute to global warming.

Coal reserves at the end of 2006,
in billions of metric tons

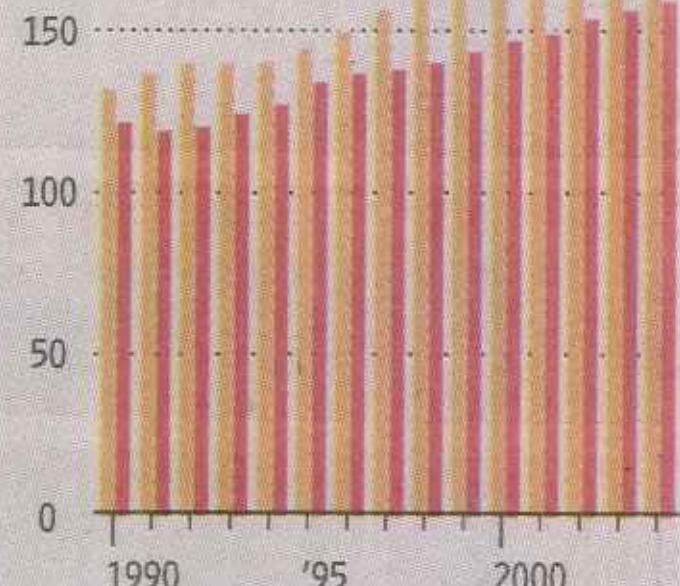
Australia's CO₂-equivalent
emissions from energy, by fuel

World total: 909 billion metric tons



Coal Petroleum and natural gas

200 million metric tons



Note: Emissions data are for years ended June 30

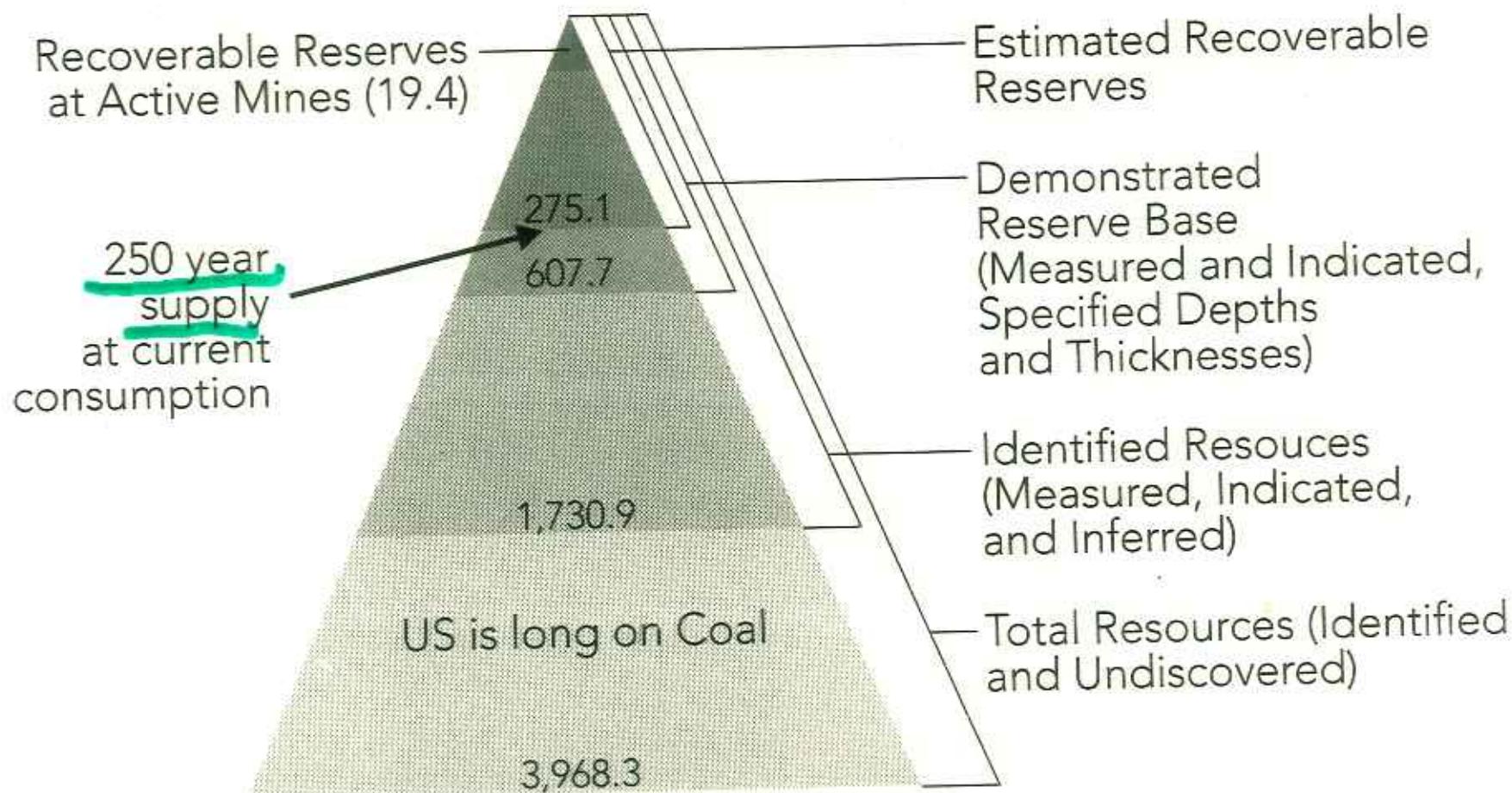
Sources: BP Statistical Review of World Energy 2007; Australian Greenhouse Office

and the expected price tag has swelled to an estimated \$1.5 bil-

burned so power plants can more easily separate the CO₂

Coal vs Energy Independence

Figure 2.
Delineation of U.S. Coal Resources and Reserves*



ethanol
wind
solar

New Monkey, Same Backs

You must choose

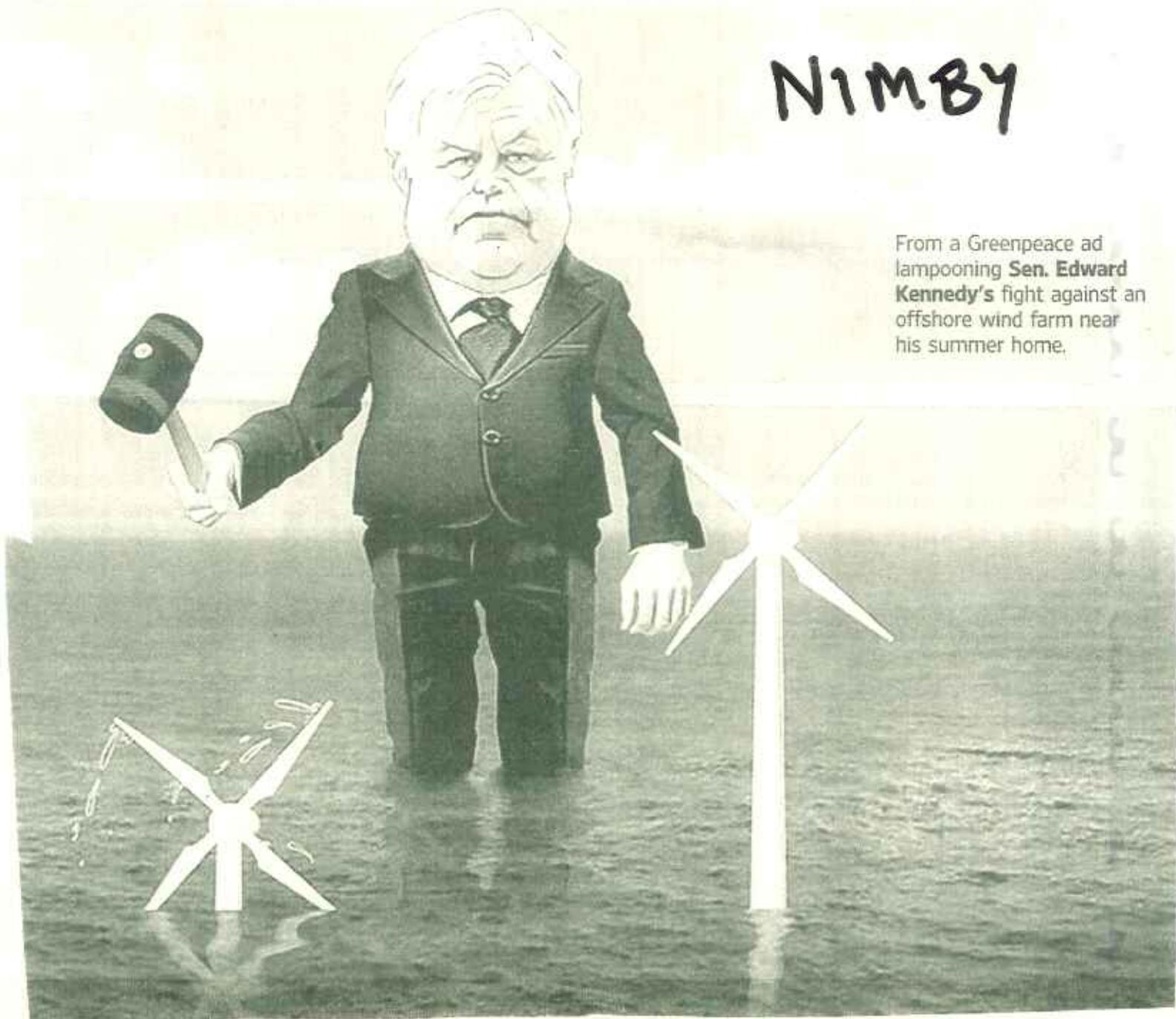
ethanol: food vs fuel

Starve the poor?

You're Blocking My View

Wind
vs
Scenic
spots
birds

NIMBY



From a Greenpeace ad
lampooning **Sen. Edward
Kennedy's** fight against an
offshore wind farm near
his summer home.

Fusion: Star in S.S. box
Modern I.C.E.

No waste

France \rightarrow 80% Power is nuclear!
vs 300 yrs.

Fossil Fuels:

Coal
N.G.
Oil

$\text{CO}_2, \text{SO}_x, \text{NO}_x, \text{radioactive elements}, \text{Hg}$

$$\eta = 1 - \frac{T_{\text{heat rejected}}}{T_{\text{heat added}}} \approx 50\%$$

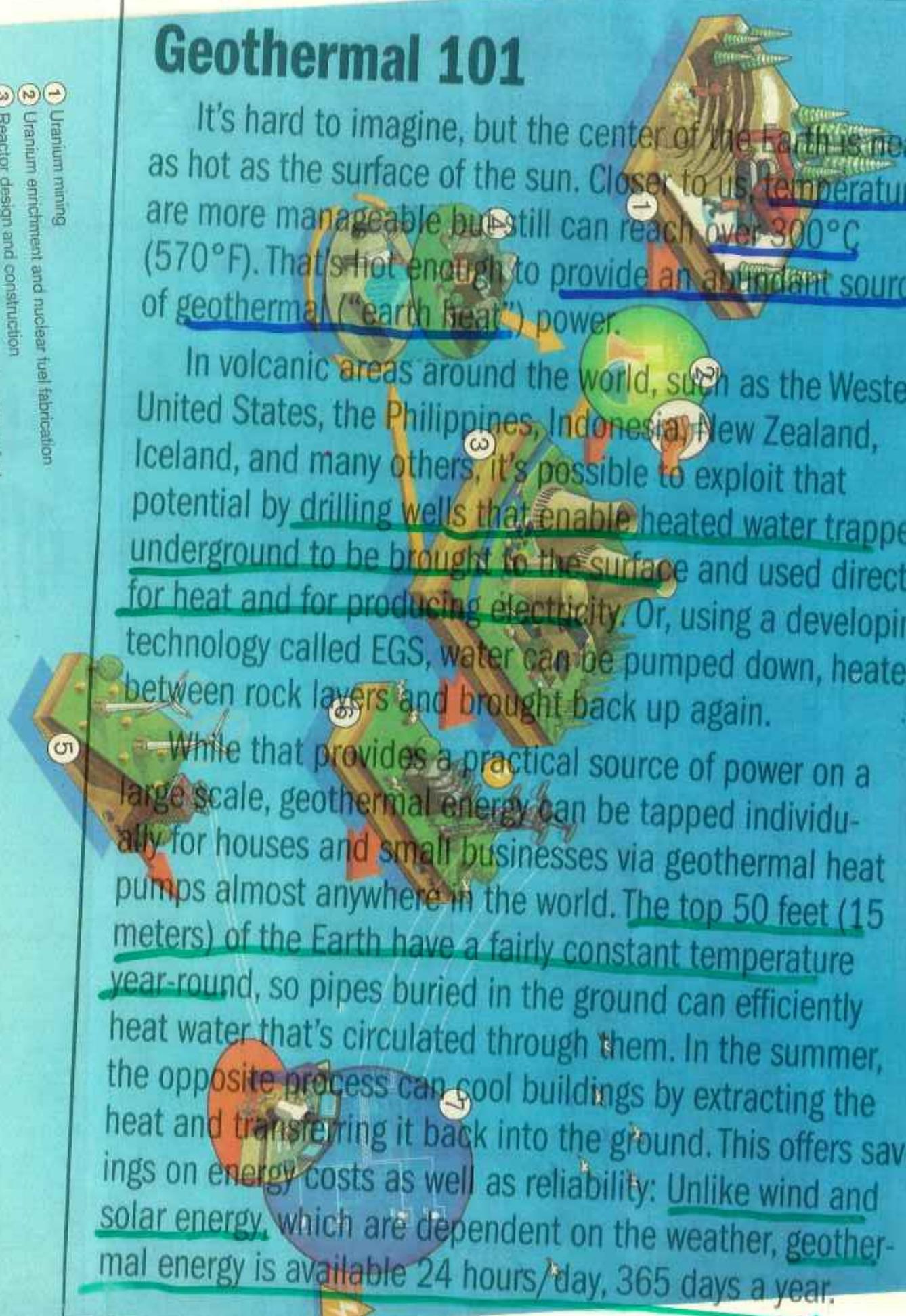
Carnot Cycle Denmark
Wind > 80%

Renewable:

$$\text{mass flow rate} = m = \rho A \bar{V}$$

$$\text{Power} = \frac{1}{2} m V^2 \sim \sqrt[3]{V_L \frac{\text{wind velocity}}{\text{velocity}}}$$

Geothermal 101

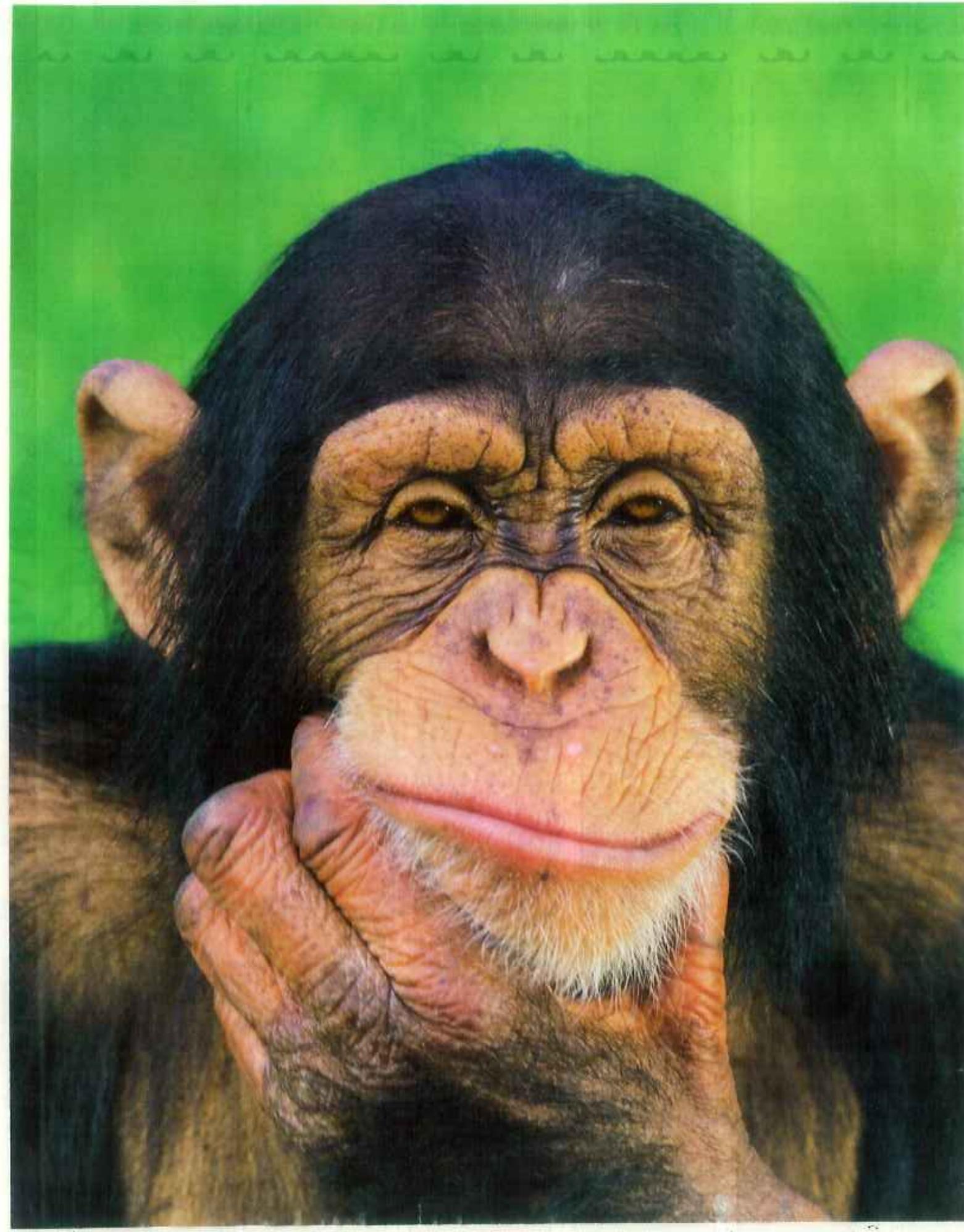


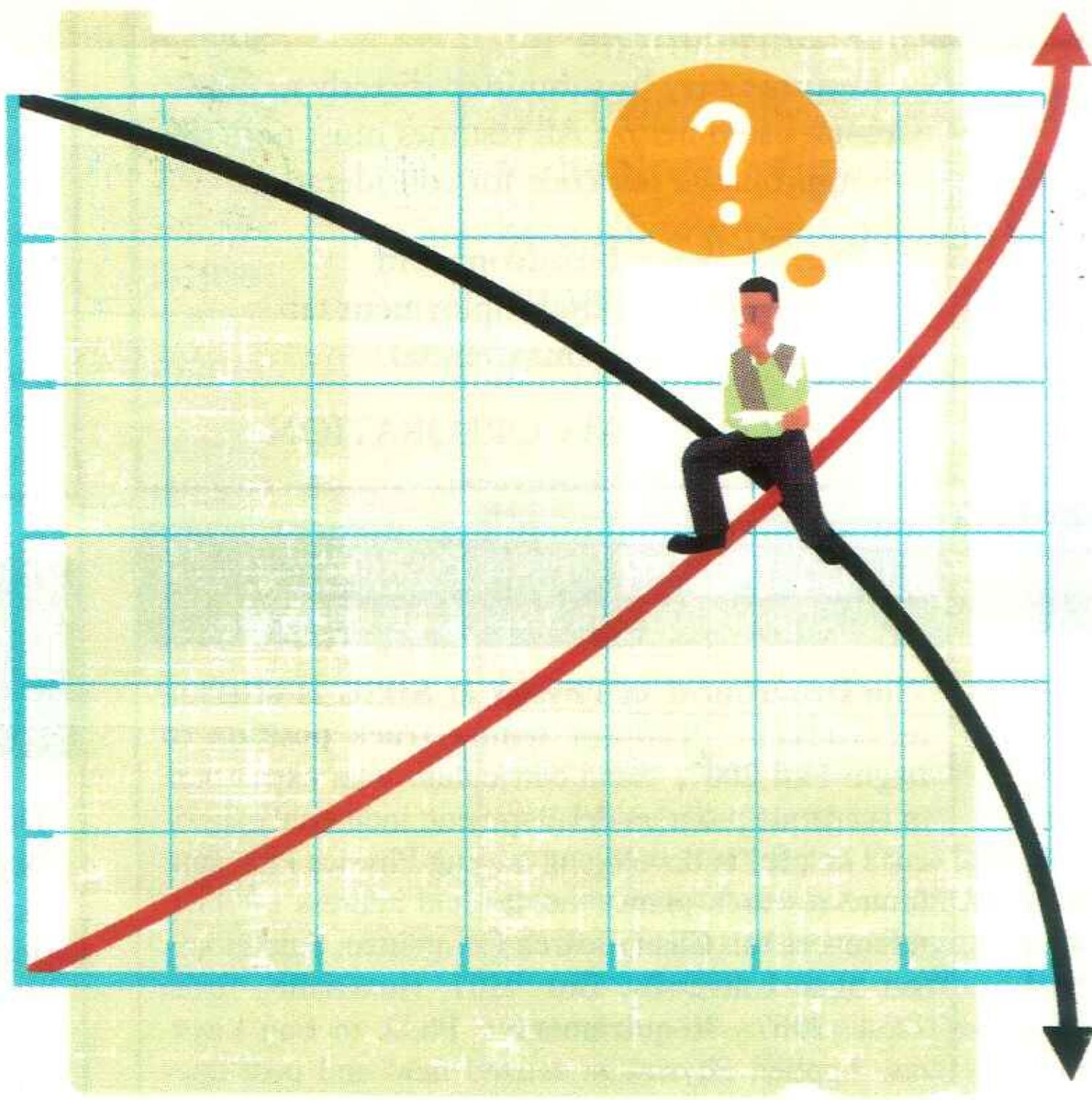
It's hard to imagine, but the center of the Earth is nearly as hot as the surface of the sun. Closer to us, temperatures are more manageable but still can reach over 300°C (570°F). That's hot enough to provide an abundant source of geothermal ("earth heat") power.

In volcanic areas around the world, such as the Western United States, the Philippines, Indonesia, New Zealand, Iceland, and many others, it's possible to exploit that potential by drilling wells that enable heated water trapped underground to be brought to the surface and used directly for heat and for producing electricity. Or, using a developing technology called EGS, water can be pumped down, heated between rock layers and brought back up again.

While that provides a practical source of power on a large scale, geothermal energy can be tapped individually for houses and small businesses via geothermal heat pumps almost anywhere in the world. The top 50 feet (15 meters) of the Earth have a fairly constant temperature year-round, so pipes buried in the ground can efficiently heat water that's circulated through them. In the summer, the opposite process can cool buildings by extracting the heat and transferring it back into the ground. This offers savings on energy costs as well as reliability: Unlike wind and solar energy, which are dependent on the weather, geothermal energy is available 24 hours/day, 365 days a year.

- 1 Uranium mining
- 2 Uranium enrichment and nuclear fuel fabrication
- 3 Reactor design and construction
- 4 Reprocessing and recycling of nuclear spent fuel
- 5 Wind power equipment
- 6 Transmission
- 7 Distribution





The Supergiants

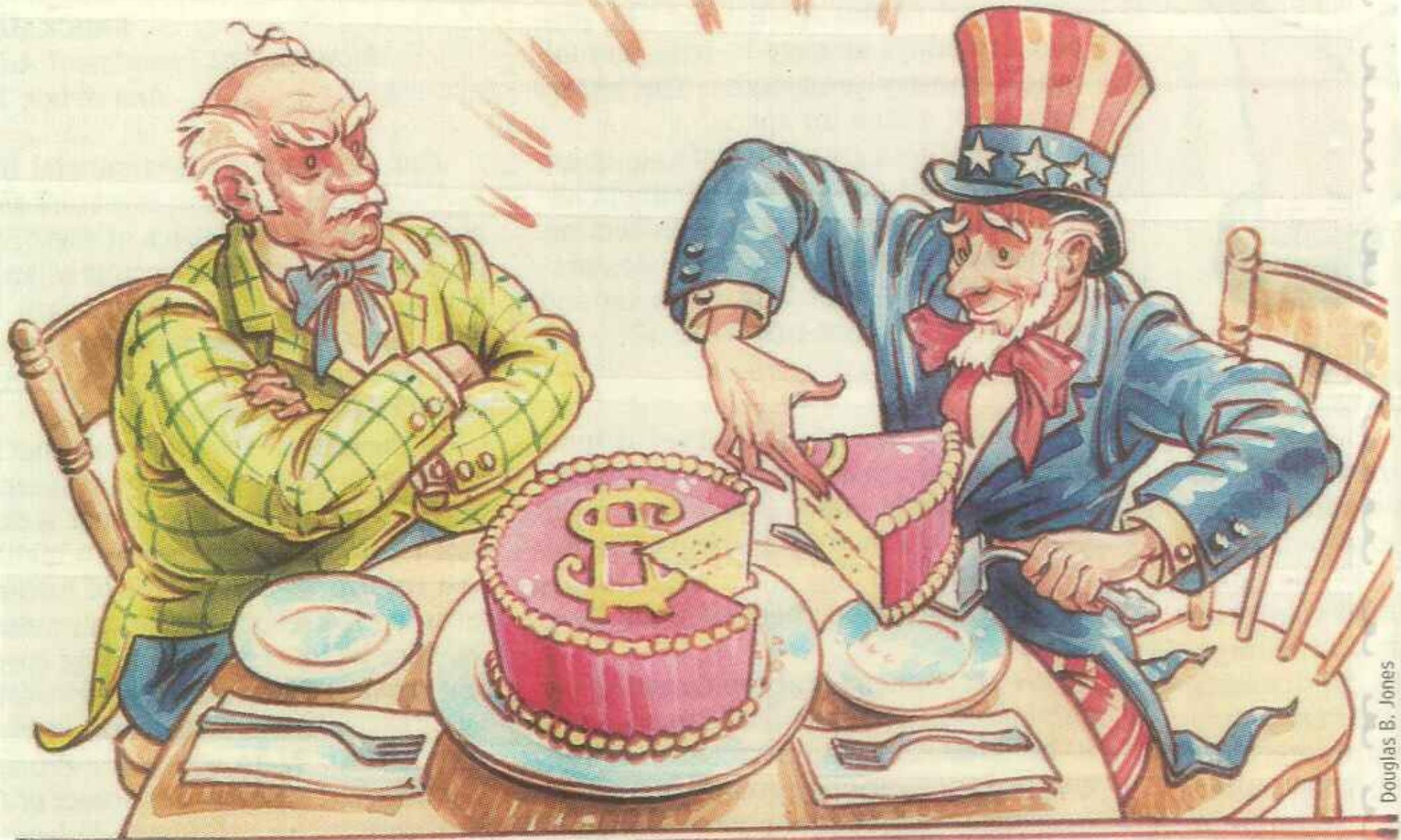
The world's largest oil fields, by remaining reserves, in billions of barrels.

Field	Country	Remaining reserves
Ghawar	Saudi Arabia	62
Safaniyah	Saudi Arabia	22
Rumaila	Iraq	17
Greater Burgan	Kuwait	16
Kashagan	Kazakhstan	13

Source: Wood Mackenzie

Iraq
Georgia

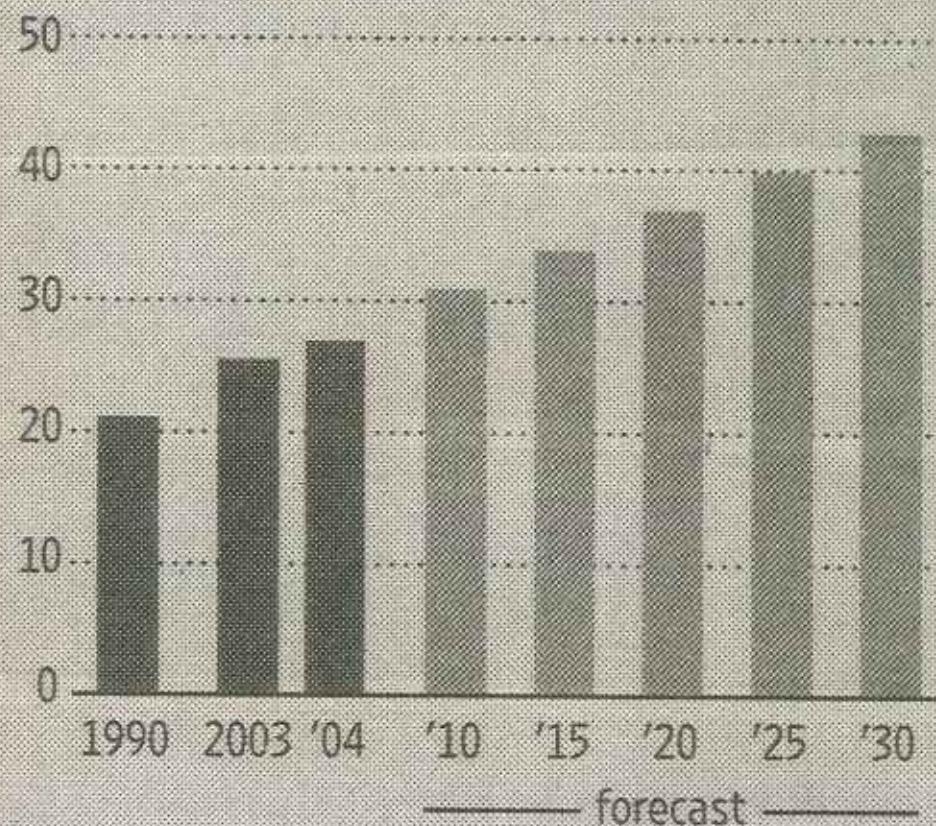




Douglas B. Jones

Hot-Button Issue

World carbon-dioxide emissions if current practices and policies remain unchanged; in billions of metric tons



Source: U.S. Energy Information Administration

❖ The Emerging Consensus:

Diplomats at global-warming talks are agreeing that much deeper cuts need to be made in the emissions that contribute to global warming.

❖ Still Under Debate:

How to apportion the cuts among countries, industries and consumers. Already, for instance, the U.S. and Australia have called for developing countries to make emissions cuts, not just the industrialized countries covered under the Kyoto agreement.

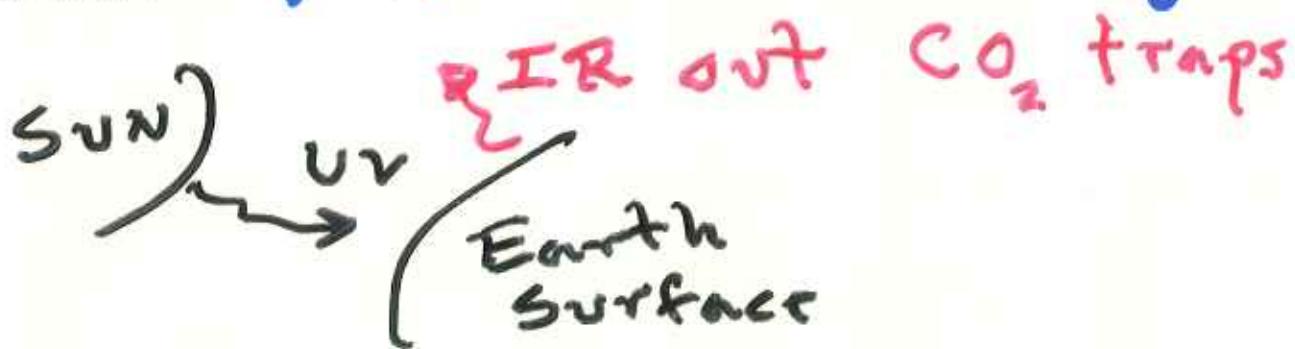
❖ What's Next:

An international fight over who gets stuck with the cleanup bill.

Power plants emit $\frac{1}{3}$ of US total CO₂

Consequences

Need CO_2 to keep earth warm; Useful next ice age?



30K ft in air $T = -50^\circ\text{C}$

Acid rain NO_x
 SO_x

Thermal: 50% heat into rivers
 lakes
Effects

Hg in oceans!

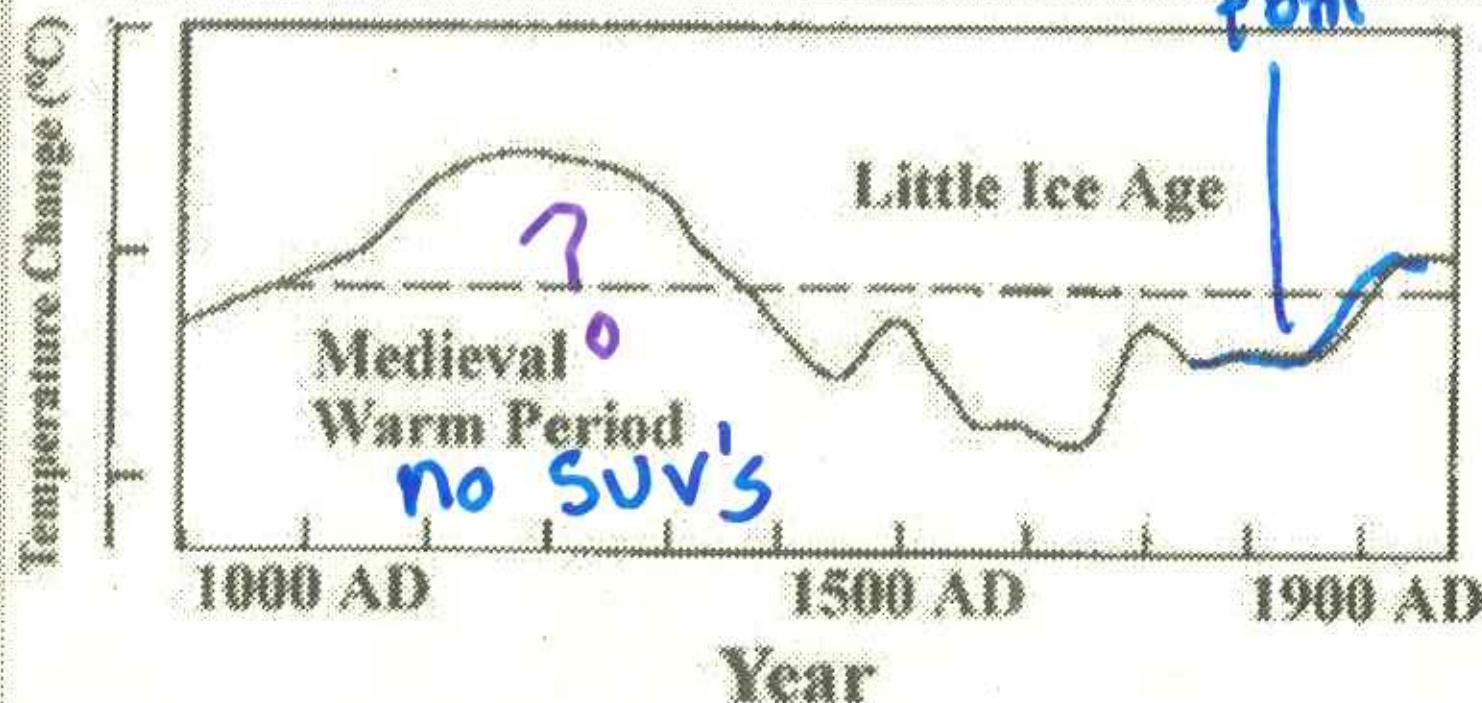


ENGLEMAN.

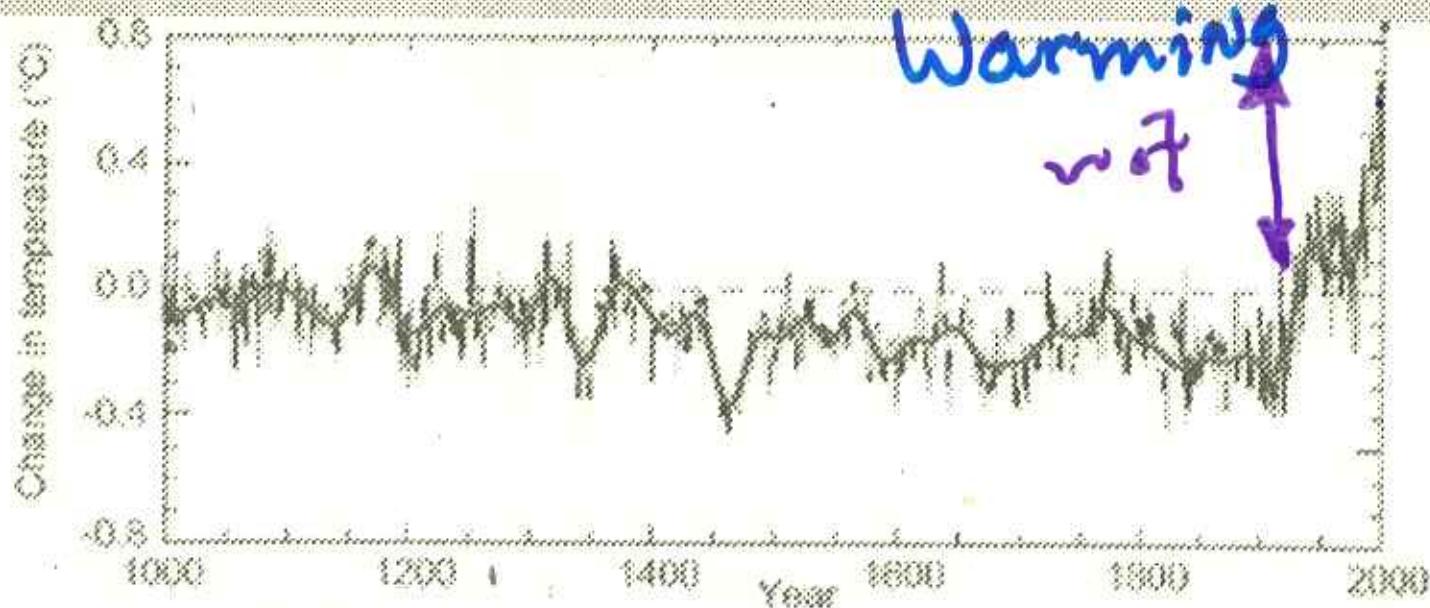
*"And please don't let global
warming affect my beach house..."*

Climate ‘Consensus’

Then ...

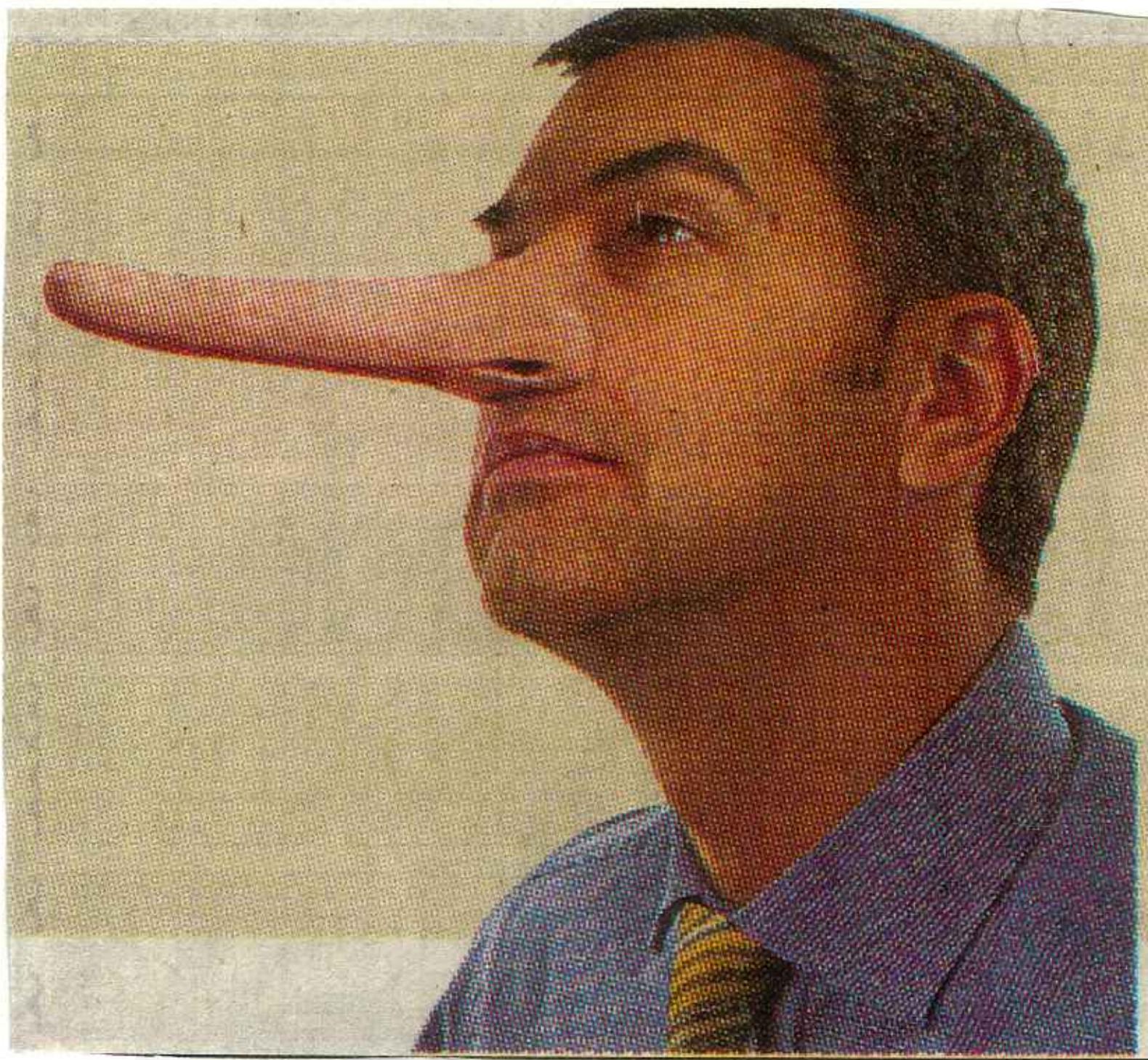


...And Now



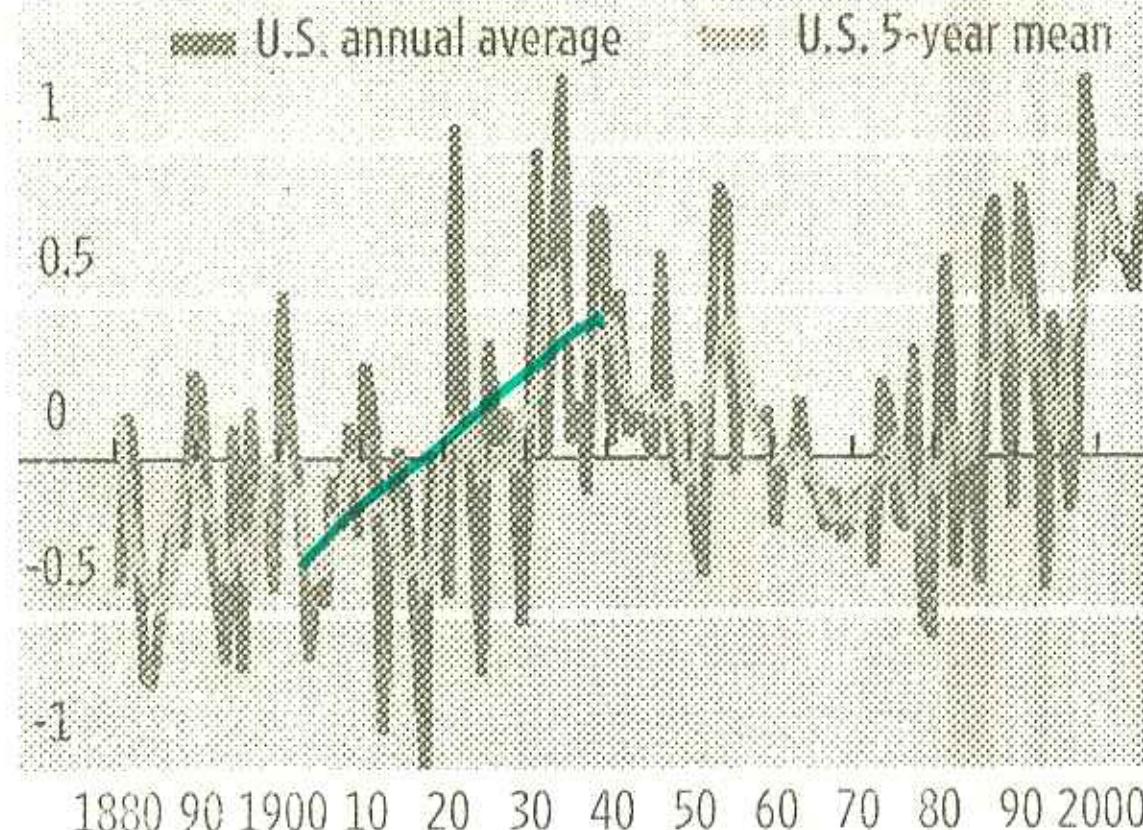
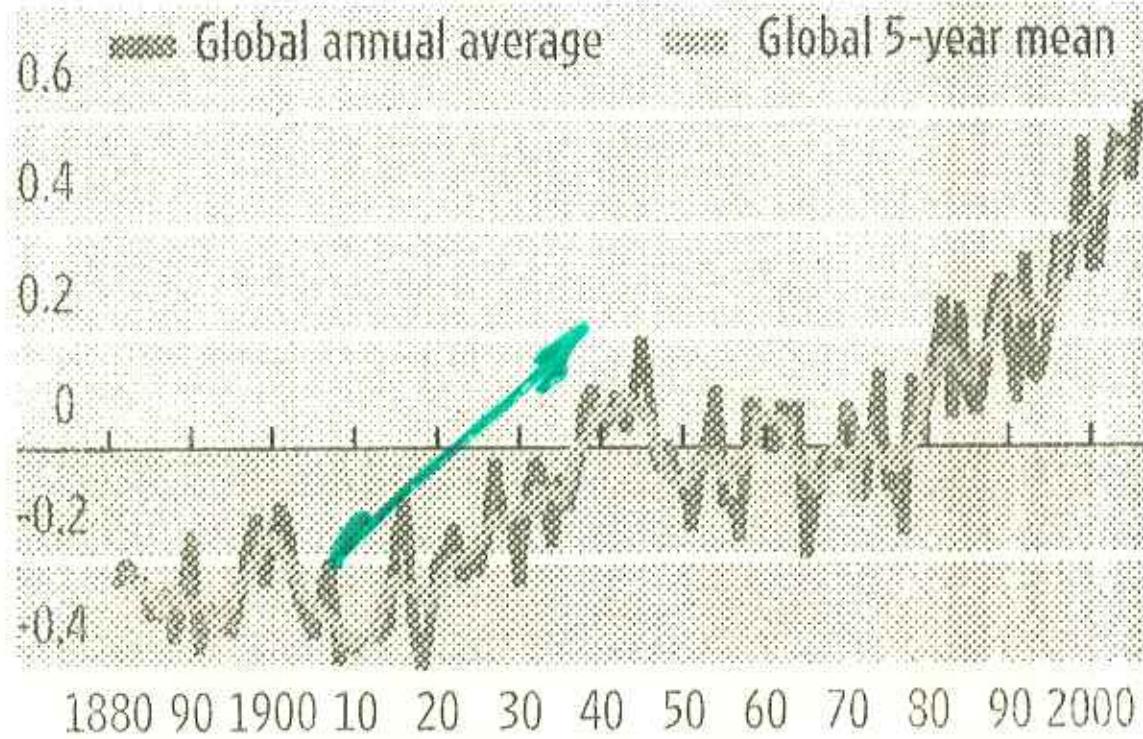
Source: Intergovernmental Panel on Climate Change

Instrumental error
till 1950's $\pm 1^{\circ}$

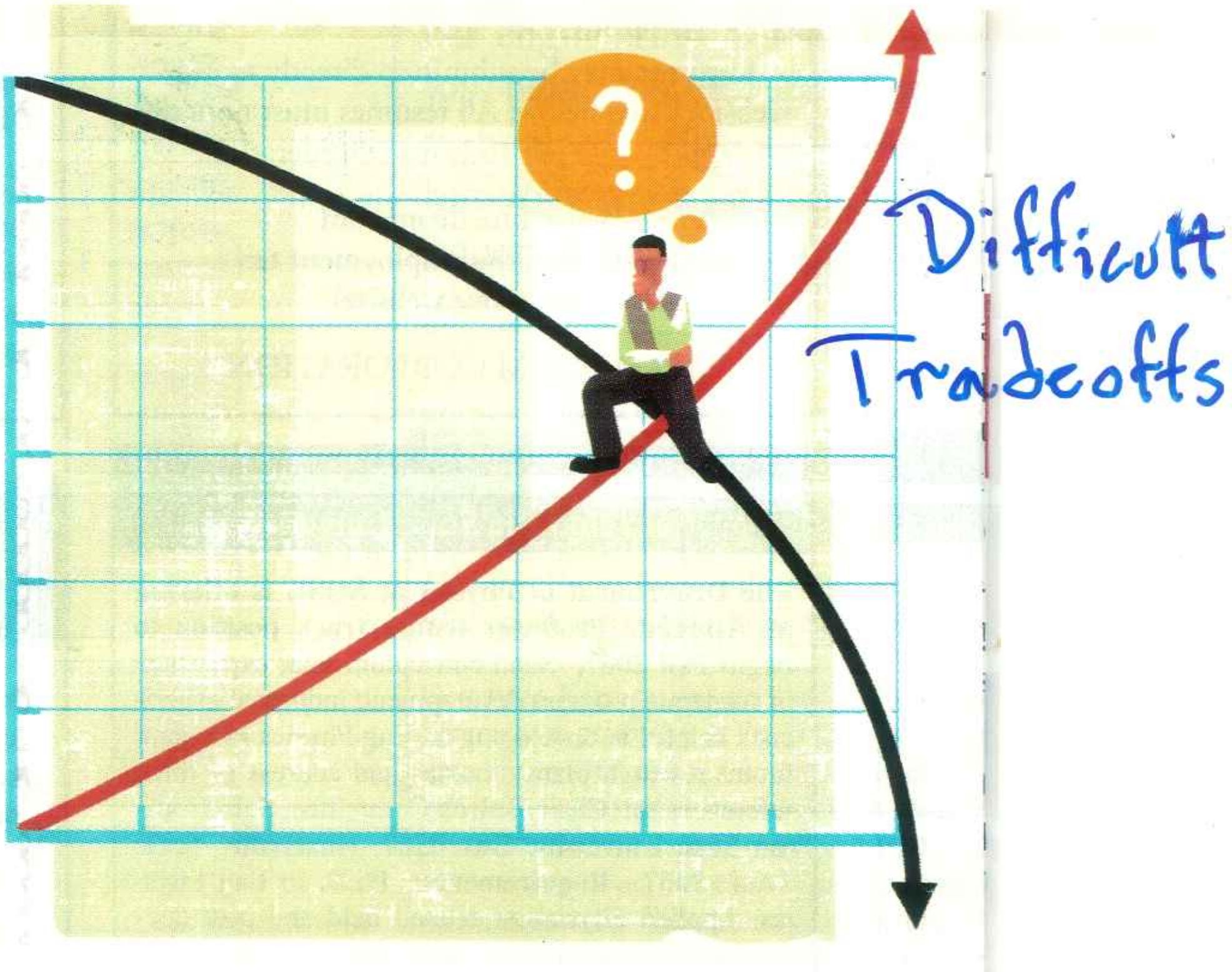


Mixed Signals

Temperature anomaly, in degrees Celsius



Source: Godard Institute for Space Studies, NASA







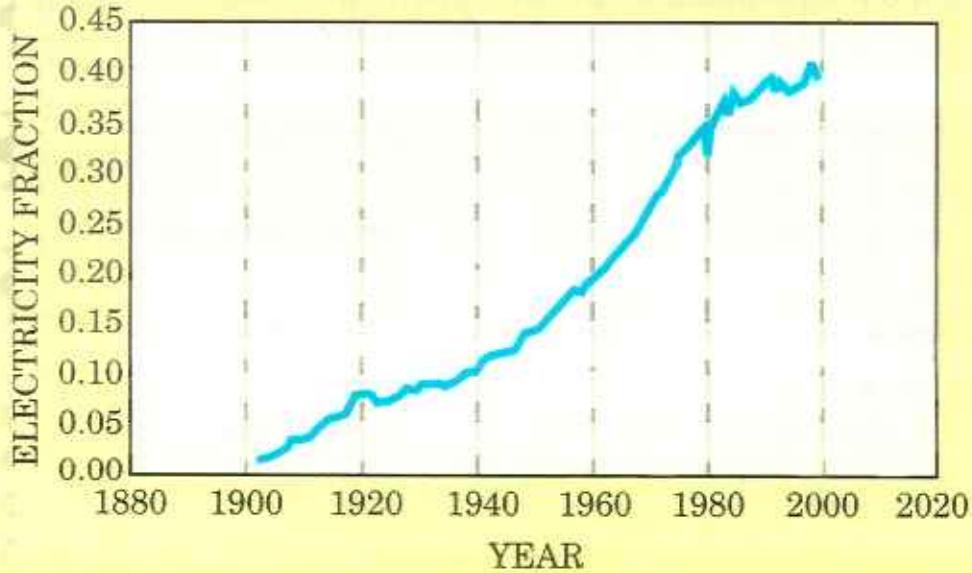


Figure 1. An increasing fraction of US energy needs over the past 100 years has been met by electricity. The same period has seen a decrease in overall energy use per dollar of gross domestic product: Electrification makes an economy more efficient.

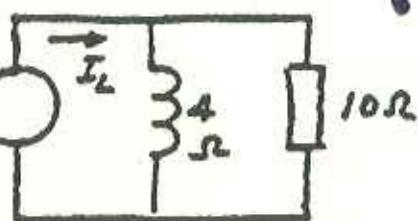
but

Using ~~S~~ P Q only Use Fig 7.25

7-15

a. 40V

a.



$$P = \frac{40^2}{10} = 160 \text{ W}$$

$$Q = \frac{40^2}{4} = 400 \text{ var}$$

$$S = \sqrt{160^2 + 400^2} = 430.8 \text{ VA}$$

7-15

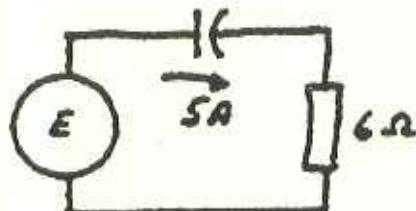
$$I_L = S/E = 430.8 / 40 = 10.77 \text{ A}$$

$$Z = E/I_L = 40 / 10.77 = 3.71 \Omega$$

b. $Q = I^2 X_C = 5^2 \times 2 = -50 \text{ var}$

$$P = I^2 R, \quad 5^2 \times 6 = 150 \text{ W}$$

$$S = \sqrt{150^2 + (-50)^2} = 158.1 \text{ VA}$$



$$E = S/I = 158.1 / 5 = 31.62 \text{ V}$$

$$Z = E/I = 31.62 / 5 = 6.32 \Omega$$

