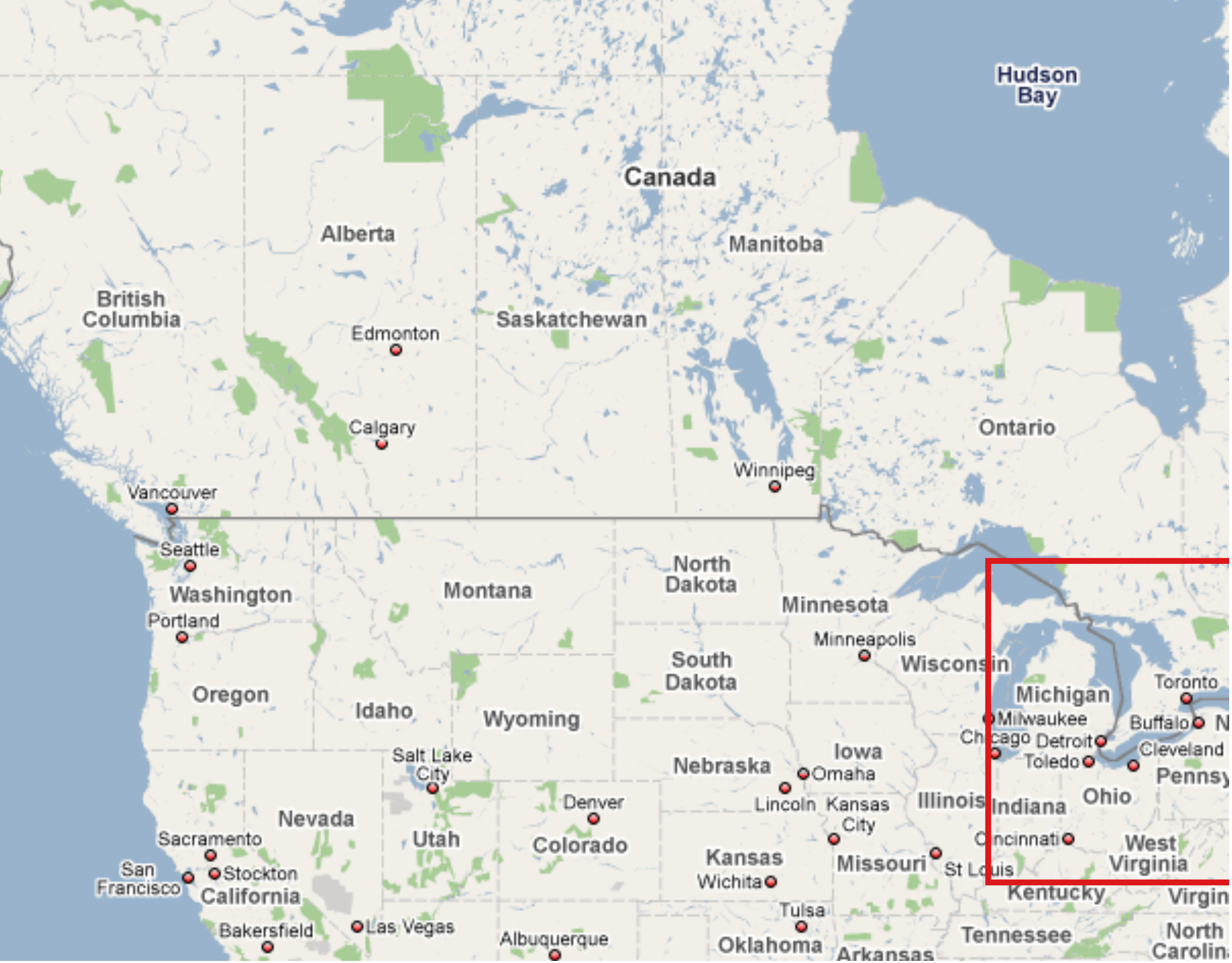
How the Internet Can Green the Gri

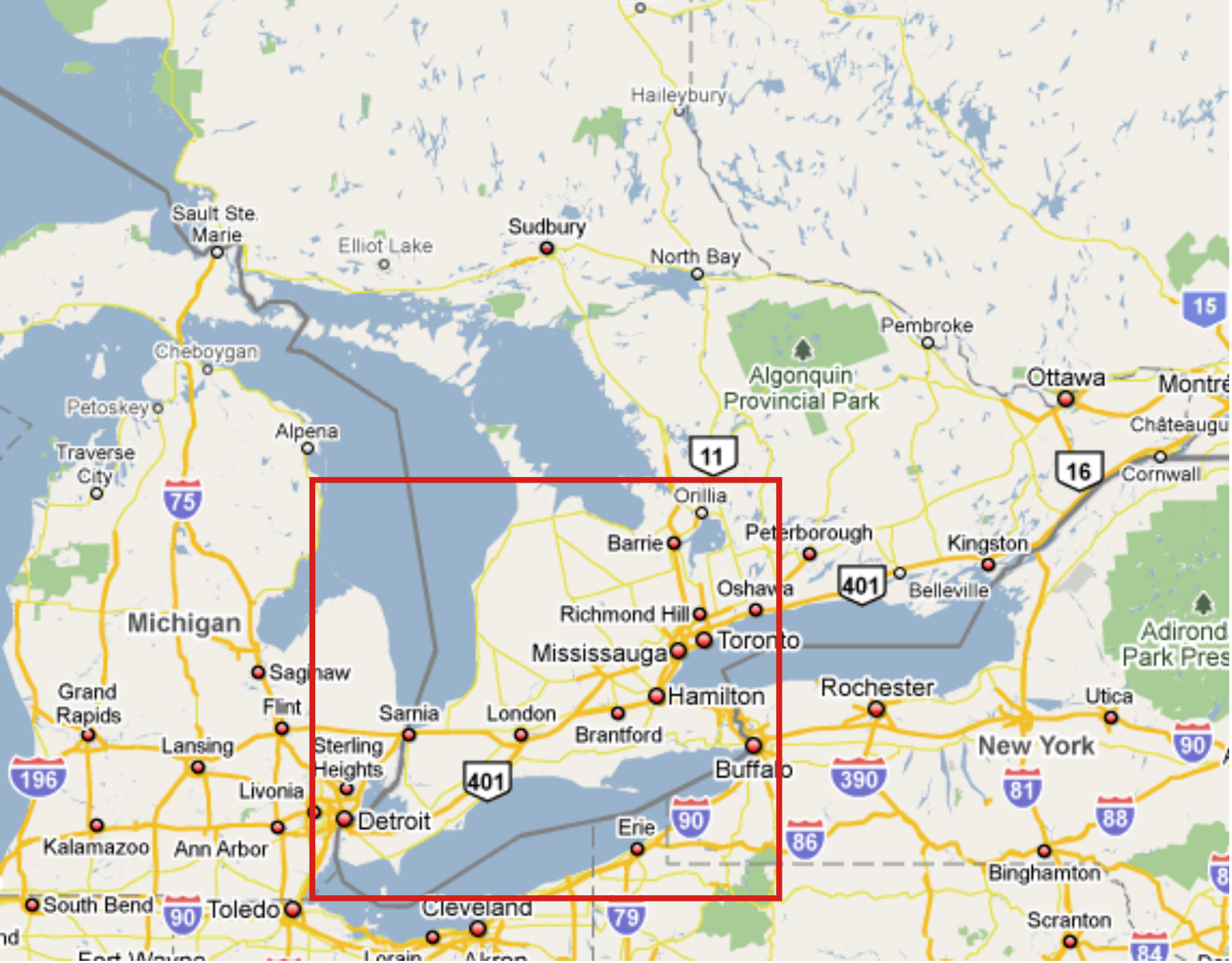
S. Keshav

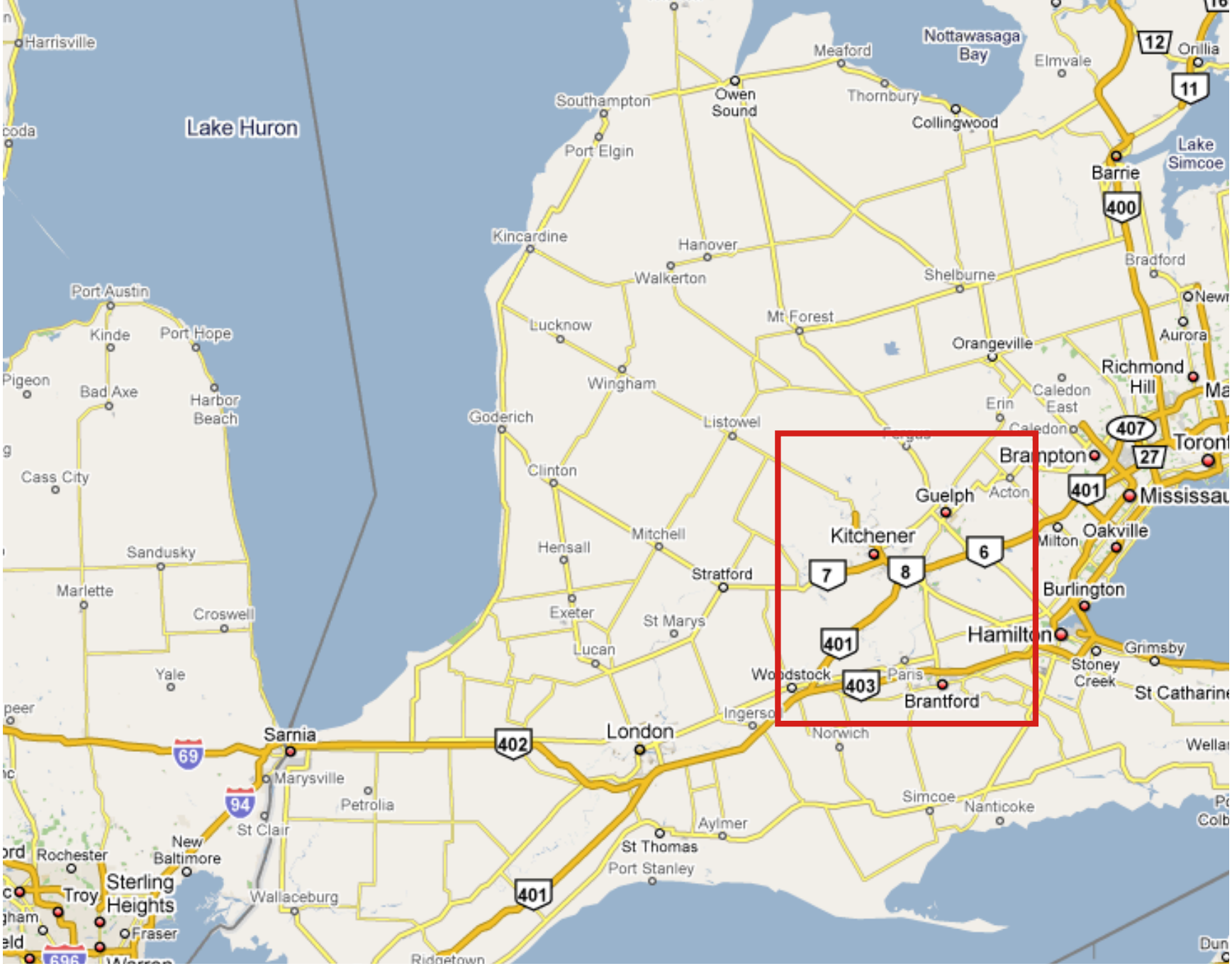
University of Waterloo

November 22, 2010

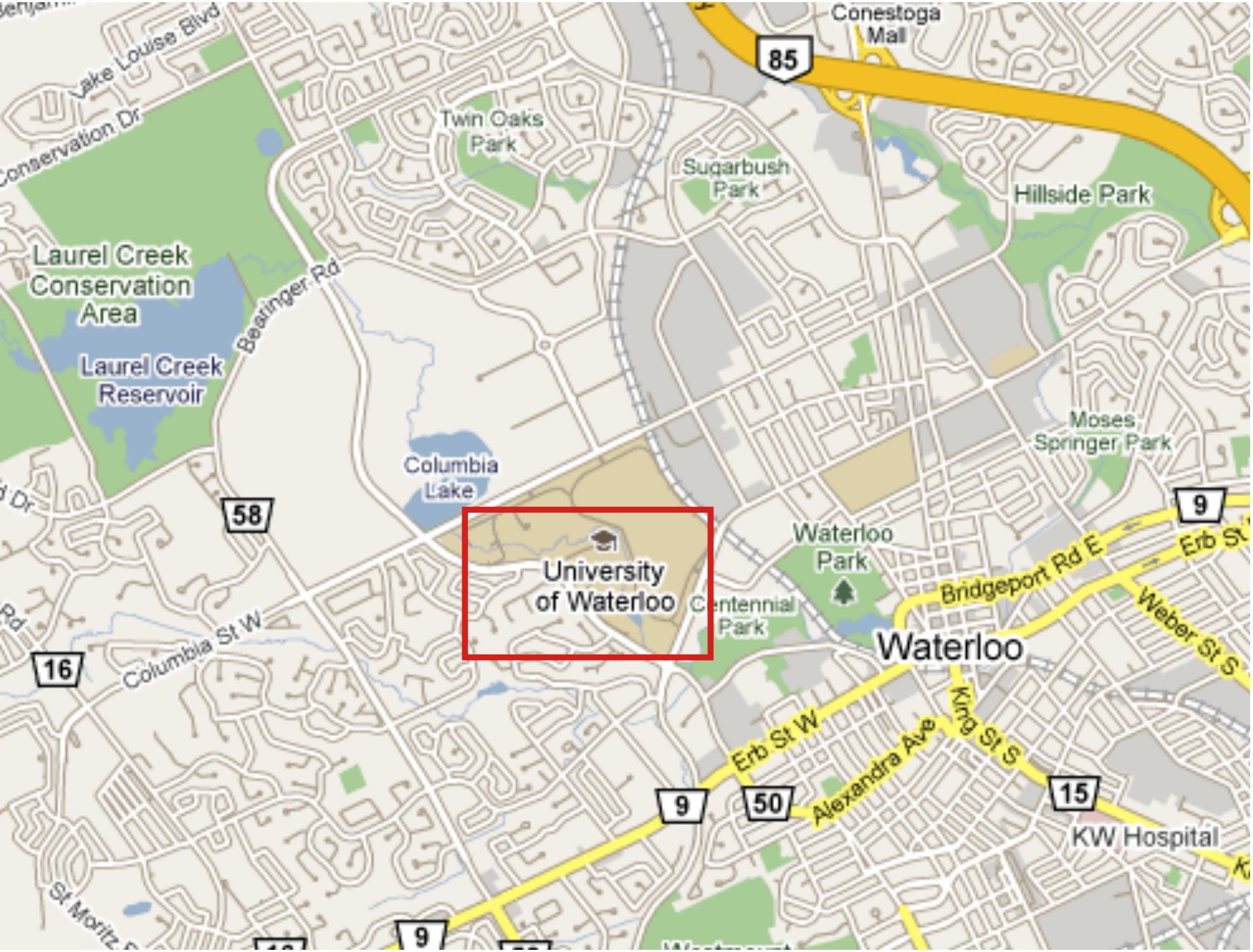
Waterloo?


Hudson Bay
Canada
Alberta
Manitoba
British Columbia
Edmonton
Saskatchewan
Calgary
Ontario
Winnipeg
Vancouver
Seattle
Washington
Portland
Montana
North Dakota
Minnesota
Minneapolis
South Dakota
Wisconsin
Michigan
Toronto
Milwaukee
Buffalo
Chicago
Detroit
Cleveland
Toledo
Oregon
Idaho
Wyoming
Salt Lake City
Nebraska
Omaha
Iowa
Lincoln
Kansas City
Illinois
Indiana
Ohio
Denver
Nevada
Utah
Colorado
Sacramento
Cincinnati
West Virginia
San Francisco
Stockton
California
Kansas
Missouri
St Louis
Wichita
Kentucky
Tulsa
Bakersfield
Las Vegas
Albuquerque
Oklahoma
Tennessee
Arkansas

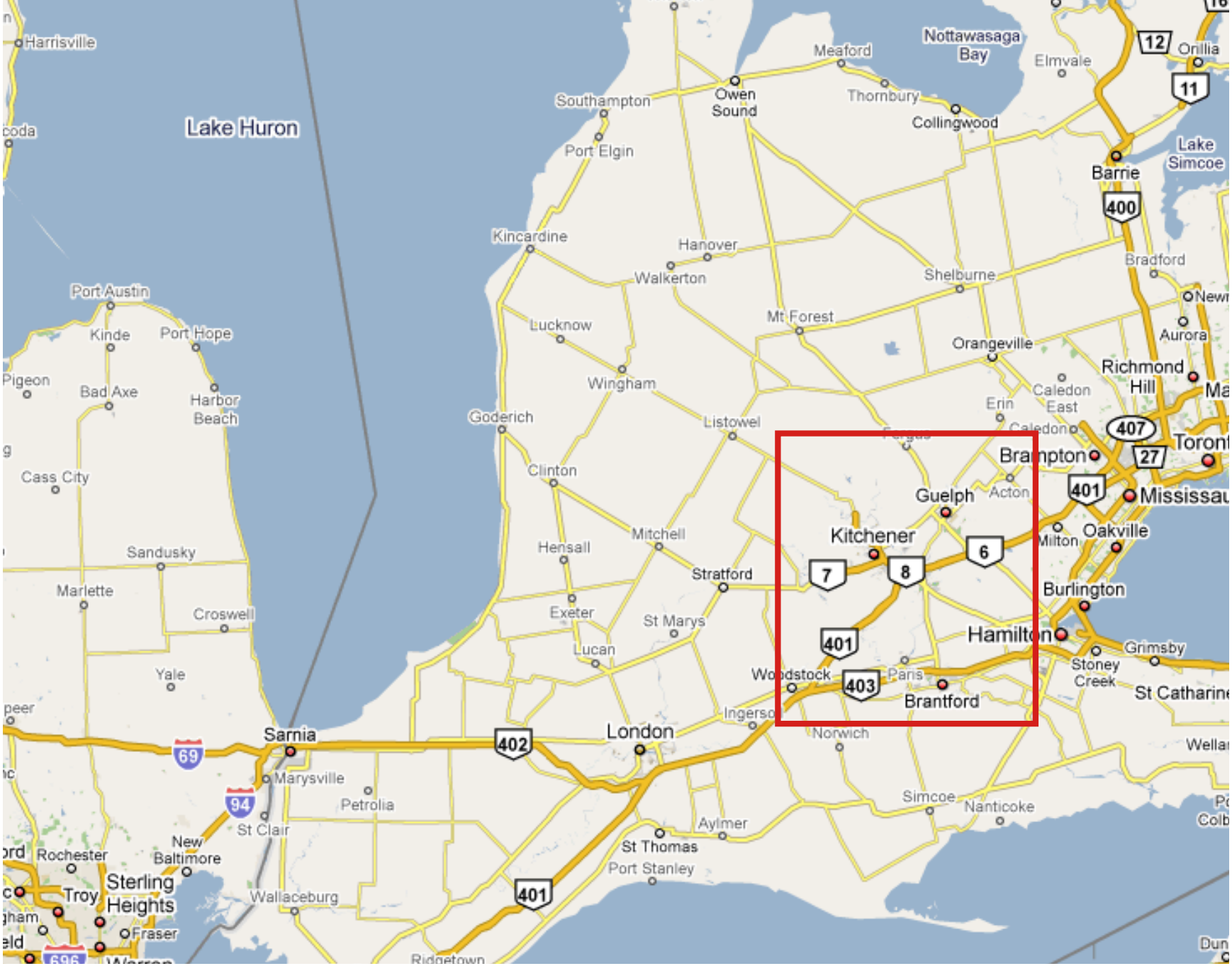

Haileybury
Sault Ste. Marie
Elliot Lake
Sudbury
North Bay
Pembroke
Cheboygan
Algonquin Provincial Park
Ottawa
Petoskey
Alpena
Traverse City
Orillia
Barrie
Peterborough
Kingston
Oshawa
Belleville
Richmond Hill
Toronto
Mississauga
Michigan
Saginaw
Hamilton
Rochester
Utica
Grand Rapids
Flint
Sarnia
London
Brantford
Lansing
Sterling Heights
Buffalo
New York
Livonia
Detroit
Erie
Kalamazoo
Ann Arbor
Binghamton
South Bend
Toledo
Cleveland
Scranton
11
16
75
401
196
90
390
81
88
86
79
15

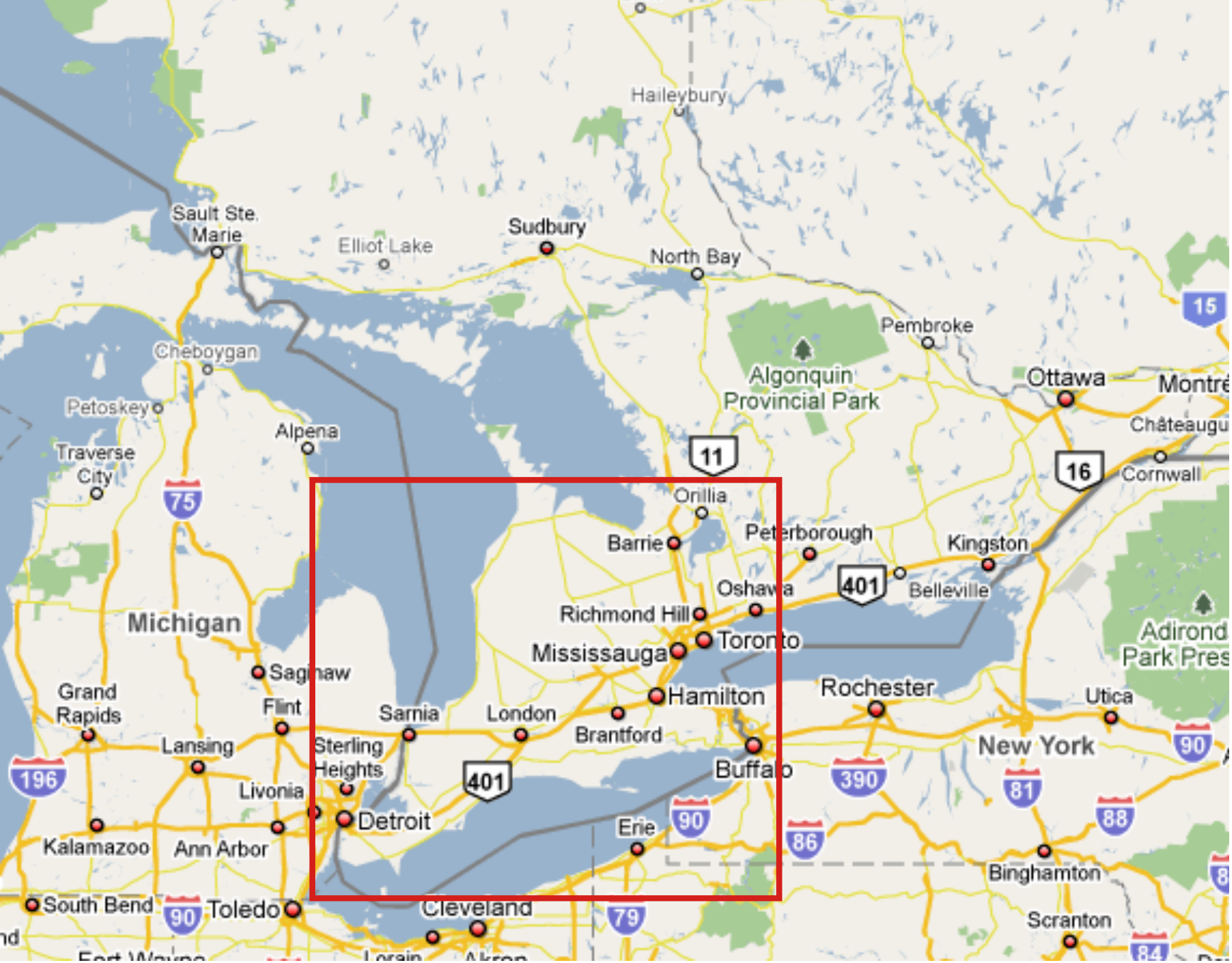

Lake Huron
Harrisville
Nottawasaga Bay
Meaford
Elmvale
Orillia
12
11
Southampton
Owen Sound
Thornbury
Collingwood
Port Elgin
Barrie
Lake Simcoe
400
Kincardine
Hanover
Walkerton
Shelburne
Bradford
Port Austin
Kinde
Port Hope
Lucknow
Mt Forest
Aurora
Orangeville
Pigeon
Bad Axe
Harbor Beach
Wingham
Richmond Hill
Caledon East
Erin
Goderich
Listowel
407
Toronto
Brampton
27
Cass City
Clinton
Guelph
Acton
401
Mississauga
Kitchener
Oakville
Milton
Sandusky
Hensall
Mitchell
6
7
8
Stratford
Burlington
Marlette
Croswell
Exeter
St Marys
Lucan
Hamilton
Grimsby
Stoney Creek
Yale
Woodstock
Paris
403
Brantford
St Catharines
Ingersoll
Norwich
Sarnia
402
London
69
Marysville
94
Petrolia
St Clair
Simcoe
Nanticoke
Aylmer
New Baltimore
Rochester
St Thomas
Port Stanley
Sterling Heights
Troy
Wallaceburg
401
Fraser
Ridgetown

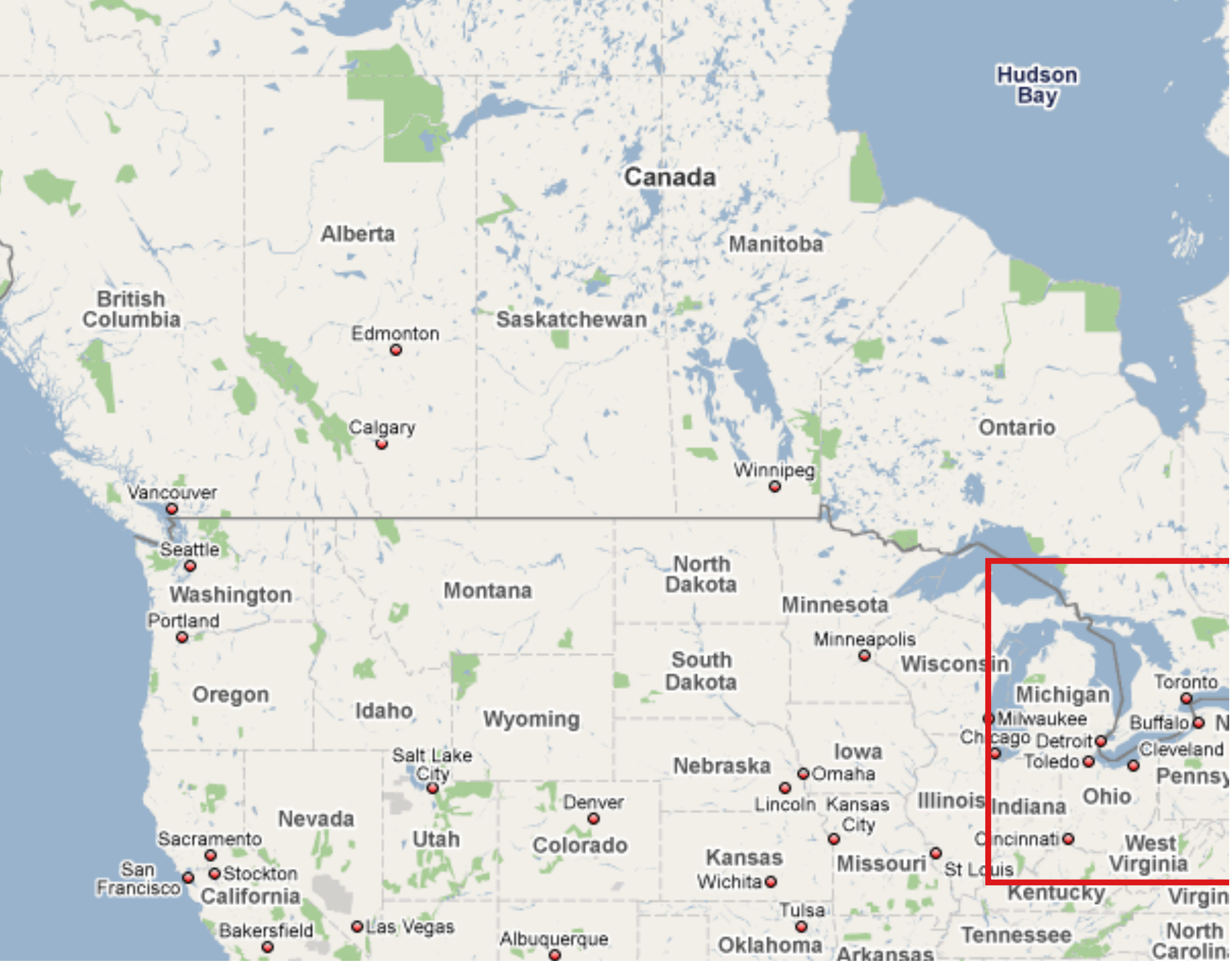

Alma
Wellington
Fergus
Elora
Floradale
6
Guelph/
Eramosa
Eramosa
7
Acton
Elmira
Woolwich
7
Guelph
86
7
24
85
Waterloo
55
Wellesley
Kitchener
401
6
Puslinch
Wilmot
7
Baden
8
Preston
24
7
Cambridge
401
8
Tavistock
North
Dumfries
24
8
Ayr
East
Zorra-Tavistock
Drumbo
Blandford-Blenheim


Conestoga Mall
85
Lake Louise Blvd
Conservation Dr
Twin Oaks Park
Sugarbush Park
Hillside Park
Laurel Creek Conservation Area
Laurel Creek Reservoir
Bearinger Rd
Columbia Lake
58
University of Waterloo
Moses Springer Park
9
Waterloo Park
Bridgeport Rd E
Erb St
Weber St S
Centennial Park
Waterloo
16
Columbia St W
Erb St W
King St S
Alexandra Ave
9
50
15
KW Hospital
St Moritz
9


Alma
Wellington
Fergus
Elora
Floradale
6
Guelph/
Eramosa
Eramosa
7
Acton
Elmira
Woolwich
7
Guelph
86
7
24
85
Waterloo
55
Wellesley
Kitchener
401
6
Puslinch
Wilmot
7
Baden
8
Preston
24
7
Cambridge
401
8
Tavistock
North
Dumfries
24
8
Ayr
East
Zorra-Tavistock
Drumbo
Blandford-Blenheim

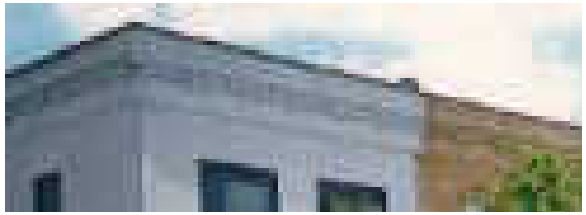

Lake Huron
Harrisville
Nottawasaga Bay
Meaford
Elmvale
Orillia
12
11
Southampton
Owen Sound
Thornbury
Collingwood
Port Elgin
Barrie
Lake Simcoe
400
Kincardine
Hanover
Walkerton
Shelburne
Bradford
Port Austin
Kinde
Port Hope
Lucknow
Mt Forest
Aurora
Orangeville
Pigeon
Bad Axe
Harbor Beach
Wingham
Richmond Hill
Caledon East
Erin
Goderich
Listowel
407
Toronto
Brampton
27
Cass City
Clinton
Guelph
Acton
401
Mississauga
Kitchener
Oakville
Milton
Sandusky
Hensall
Mitchell
6
7
8
Stratford
Burlington
Marlette
Croswell
Exeter
St Marys
Lucan
Hamilton
Grimsby
Stoney Creek
Yale
Woodstock
Paris
403
Brantford
St Catharines
Ingersoll
Norwich
Sarnia
402
London
69
Marysville
94
Petrolia
St Clair
Simcoe
Nanticoke
Aylmer
New Baltimore
Rochester
St Thomas
Port Stanley
Sterling Heights
Troy
Wallaceburg
401
Fraser
Ridgetown


Haileybury
Sault Ste. Marie
Elliot Lake
Sudbury
North Bay
Pembroke
Cheboygan
Algonquin Provincial Park
Ottawa
Petoskey
Alpena
Traverse City
Orillia
Barrie
Peterborough
Kingston
Oshawa
Belleville
Richmond Hill
Toronto
Mississauga
Michigan
Saginaw
Hamilton
Rochester
Utica
Grand Rapids
Flint
Sarnia
London
Brantford
Lansing
Sterling Heights
Buffalo
New York
Livonia
Detroit
Erie
Kalamazoo
Ann Arbor
Binghamton
South Bend
Toledo
Cleveland
Scranton
11
16
75
401
196
90
390
81
88
86
79
15


Hudson Bay
Canada
Alberta
Manitoba
British Columbia
Edmonton
Saskatchewan
Calgary
Ontario
Winnipeg
Vancouver
Seattle
Washington
Portland
Montana
North Dakota
Minnesota
Minneapolis
South Dakota
Wisconsin
Michigan
Toronto
Milwaukee
Buffalo
Chicago
Detroit
Cleveland
Toledo
Oregon
Idaho
Wyoming
Salt Lake City
Nebraska
Omaha
Iowa
Lincoln
Kansas City
Illinois
Indiana
Ohio
Denver
Nevada
Utah
Colorado
Sacramento
Cincinnati
West Virginia
San Francisco
Stockton
California
Kansas
Missouri
St Louis
Wichita
Kentucky
Tulsa
Bakersfield
Las Vegas
Albuquerque
Oklahoma
Tennessee
Arkansas

Home of WATF
RIM/Blackberry

~25,000 studer
~200 Math facu
~70 CS faculty
~2000 CS unde



Pop Quiz

Das Kapital.

Kritik der politischen Oekonomie.

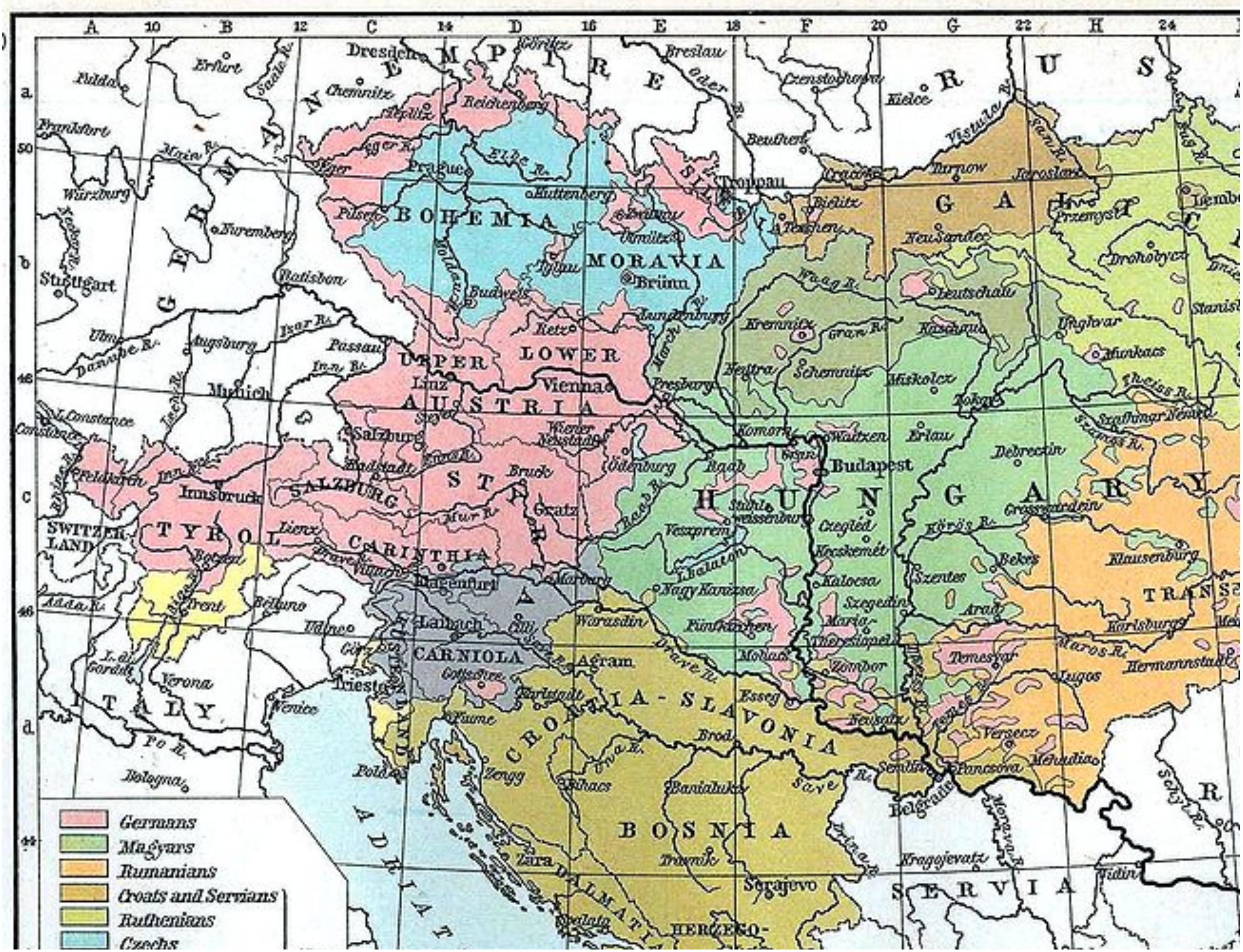
Von

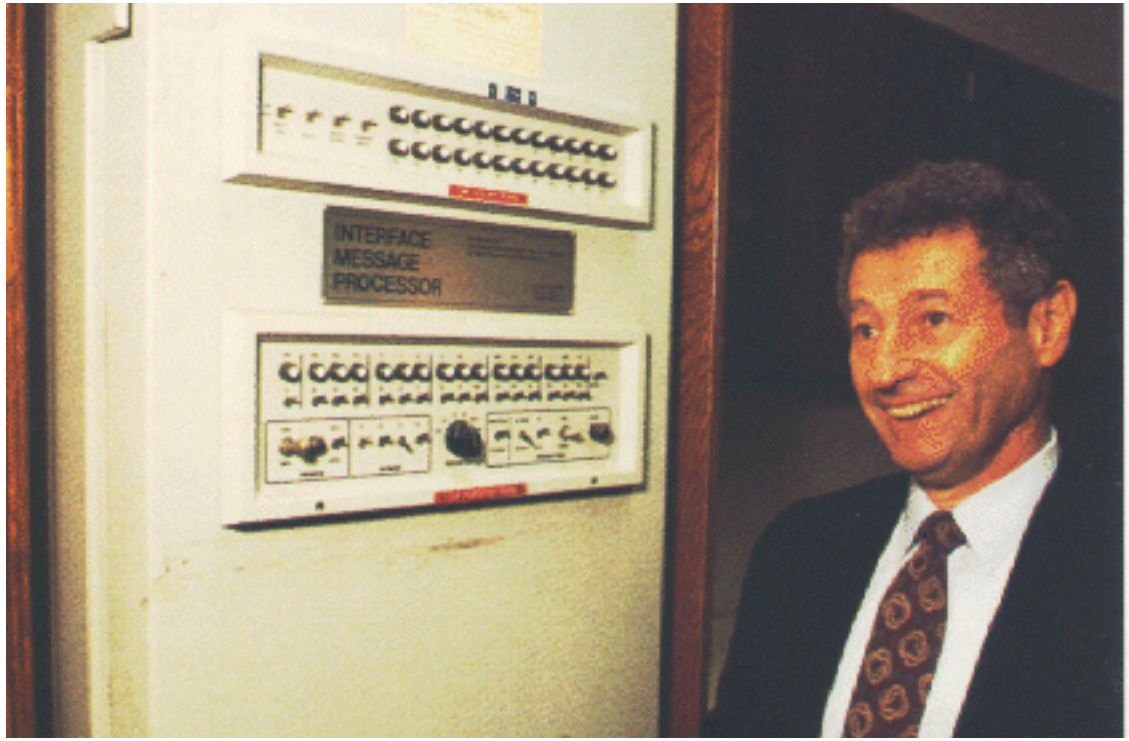
Karl Marx.

Erster Band.

Buch I: Der Produktionsprocess des Kapitals.

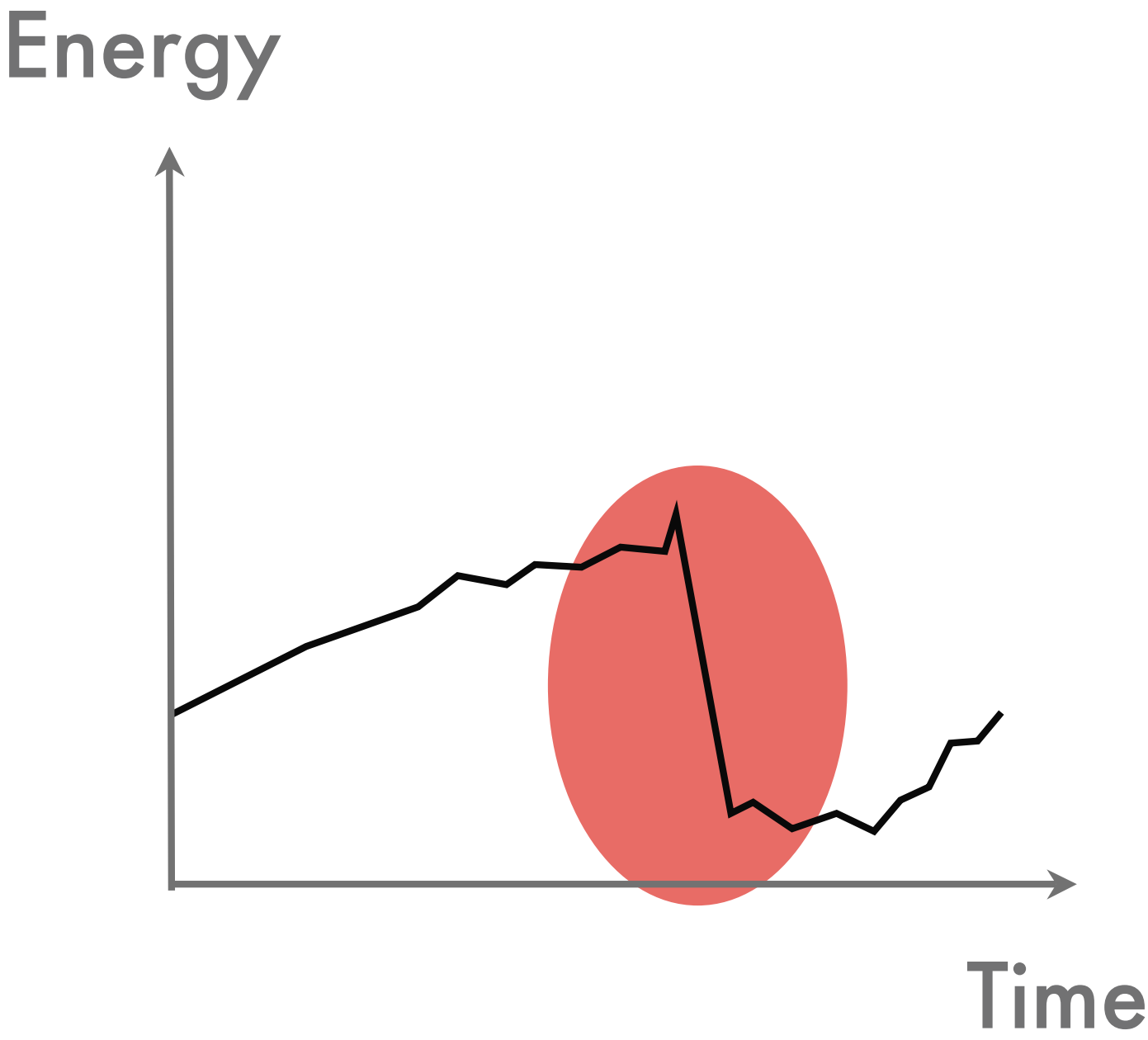
Hamburg
Verlag von Otto Meissner.
1867.


Germans
Magyars
Rumanians
Croats and Servians
Ruthenians
Czechs
BOHEMIA
MORAVIA
UPPER
LOWER
AUSTRIA
SALZBURG
TYROL
CARINTHIA
CARNIOLA
HUNGARY
CROATIA-SLAVONIA
BOSNIA
DALMATIA
SERVIA
SWITZERLAND
ITALY
Vienna
Budapest
Prague
Brünn
Innsbruck
Gratz
Trieste
Agram
Belgrade
Serajevo
Zara
Fiume
Dresden
Munich
Stuttgart
Nuremberg
Salzburg
Linz
Laibach
Klausenburg
Debreczin
Szegedin
Temesvar
Hermannstadt
Troppau
Verona
Venice
Bologna
Trent

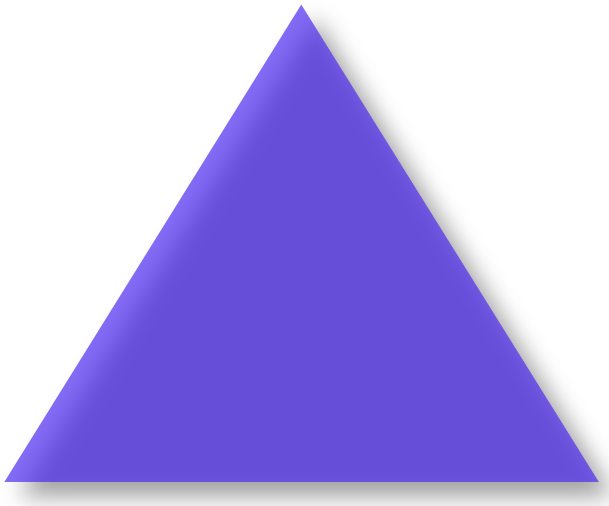

INTERFACE
MESSAGE
PROCESSOR


Xerox Alto II, US, 1974
(102626737)


ACHTUNG!
SIE VERLASSEN
WEST BERLIN


Energy
Time

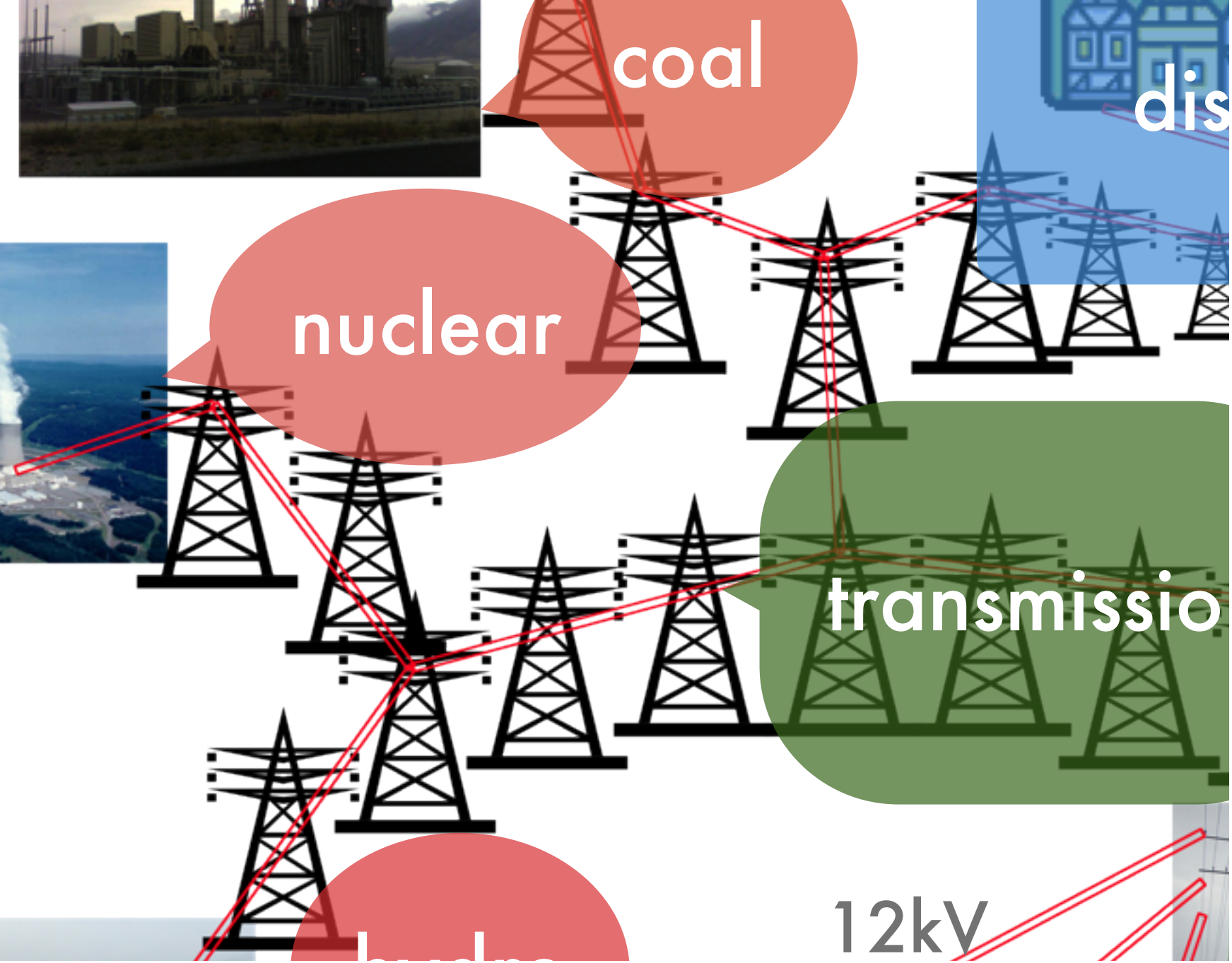
Internal contradictions



External pressures

Technologica

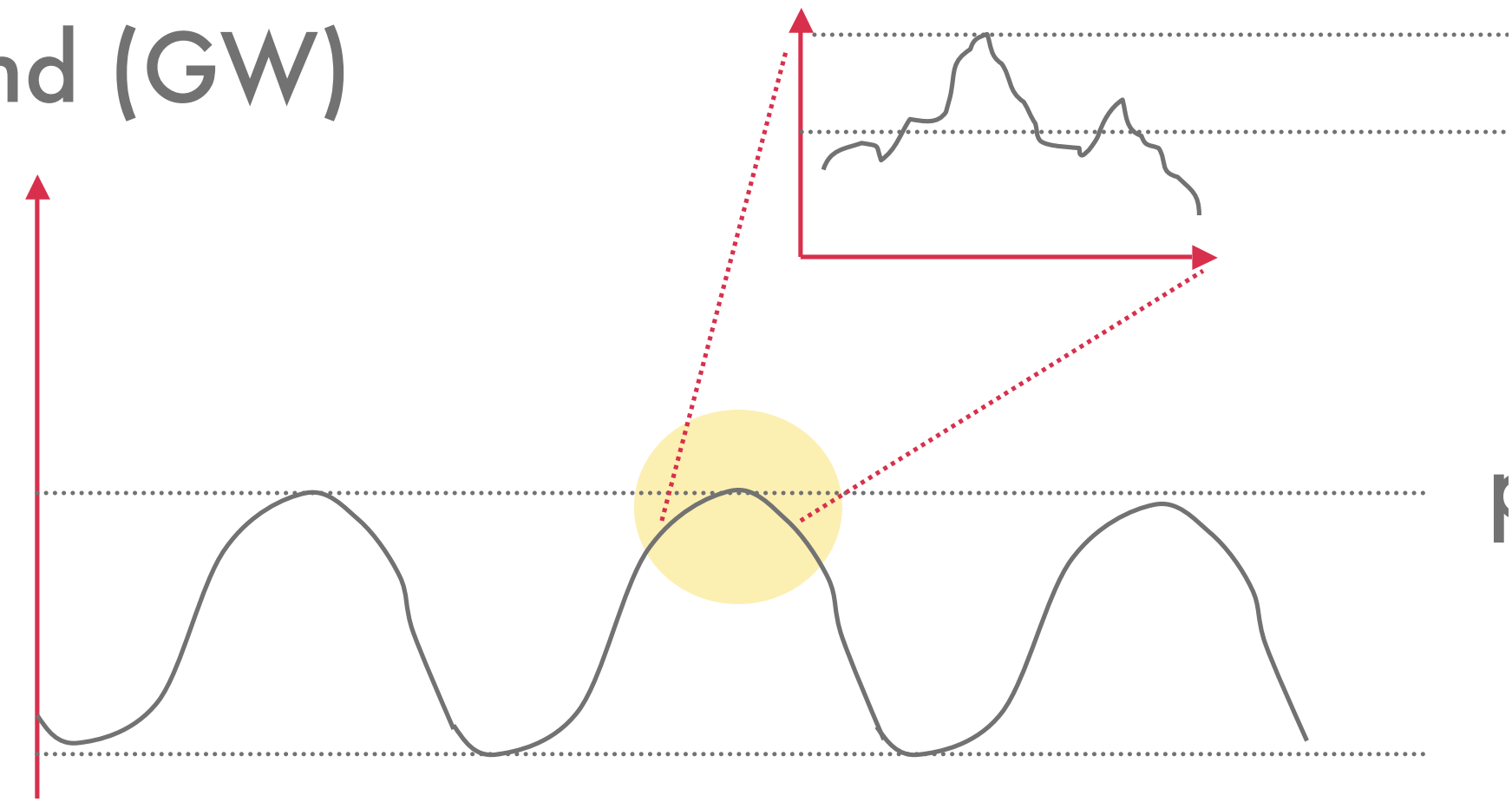
Grid for dummi


coal
dis
nuclear
transmissio
12kV

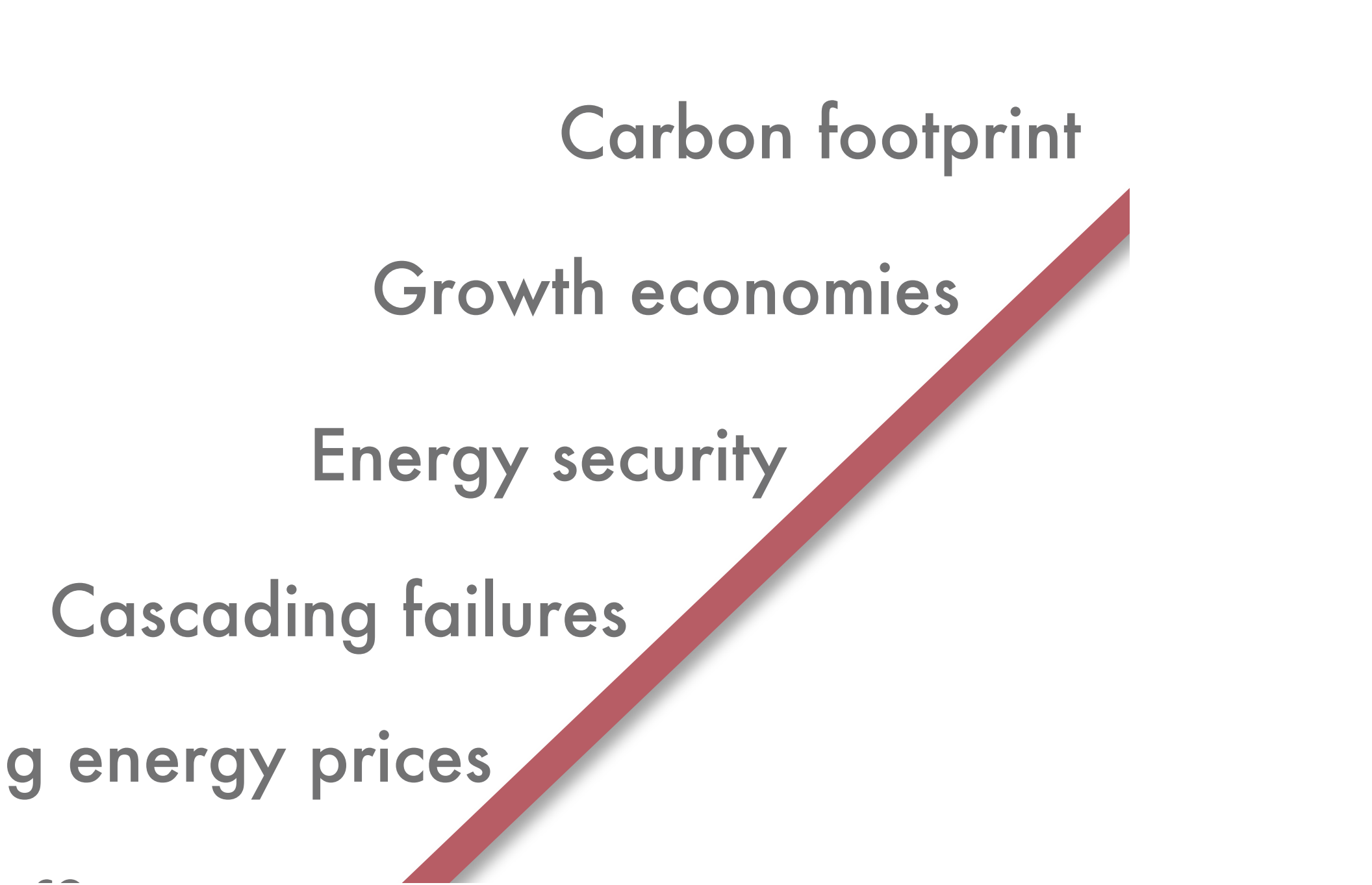
Fundamental const

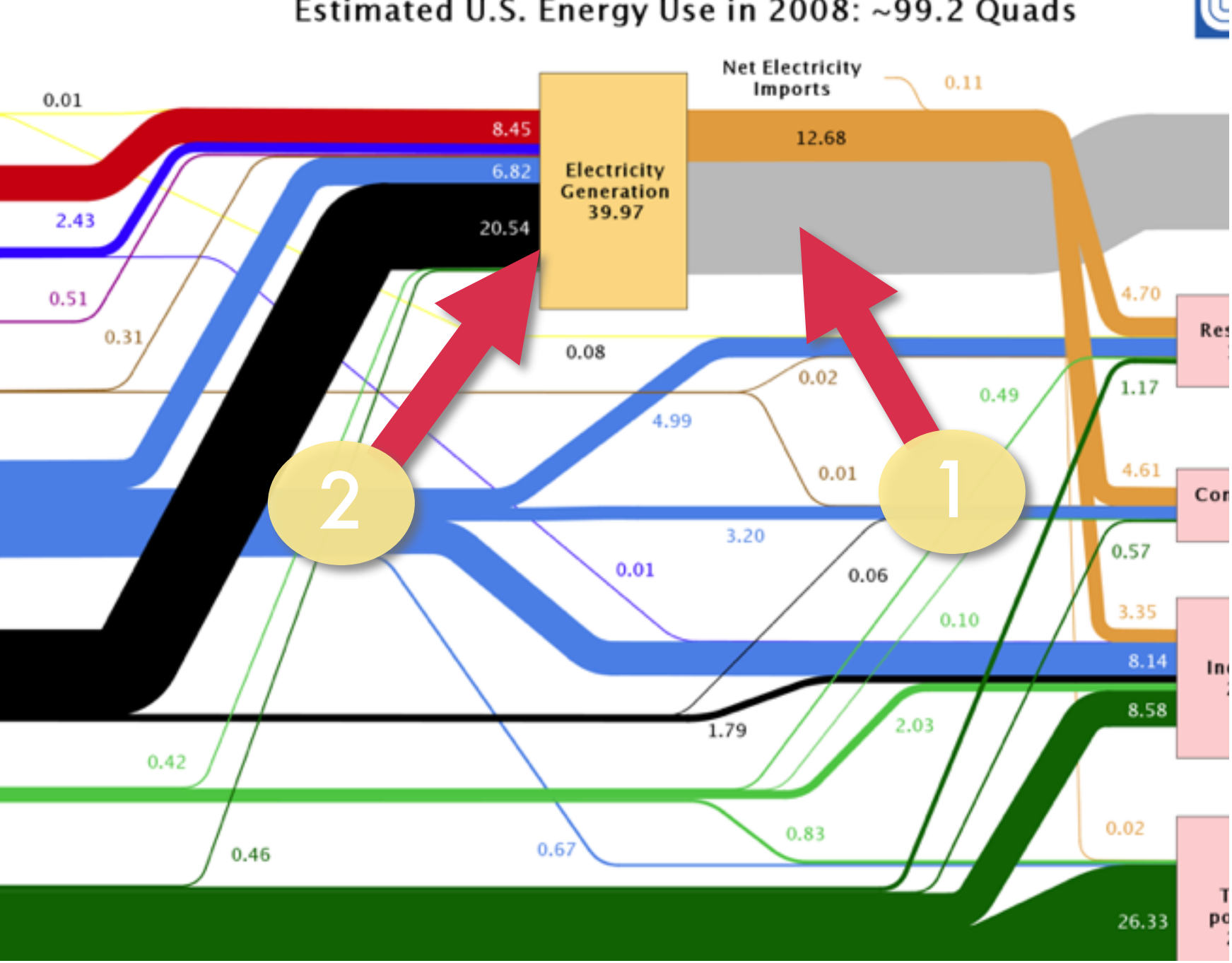
- Generation = Load

Power markets



Impending crisi


Carbon footprint
Growth economies
Energy security
Cascading failures
g energy prices


Estimated U.S. Energy Use in 2008: ~99.2 Quads
Net Electricity Imports
0.11
12.68
Electricity Generation 39.97
0.01
8.45
6.82
2.43
20.54
0.51
0.31
0.08
0.02
0.49
4.99
0.01
3.20
0.01
0.06
0.10
1.79
2.03
0.42
0.83
0.67
0.46
4.70
1.17
4.61
0.57
3.35
8.14
8.58
0.02
26.33
2
1

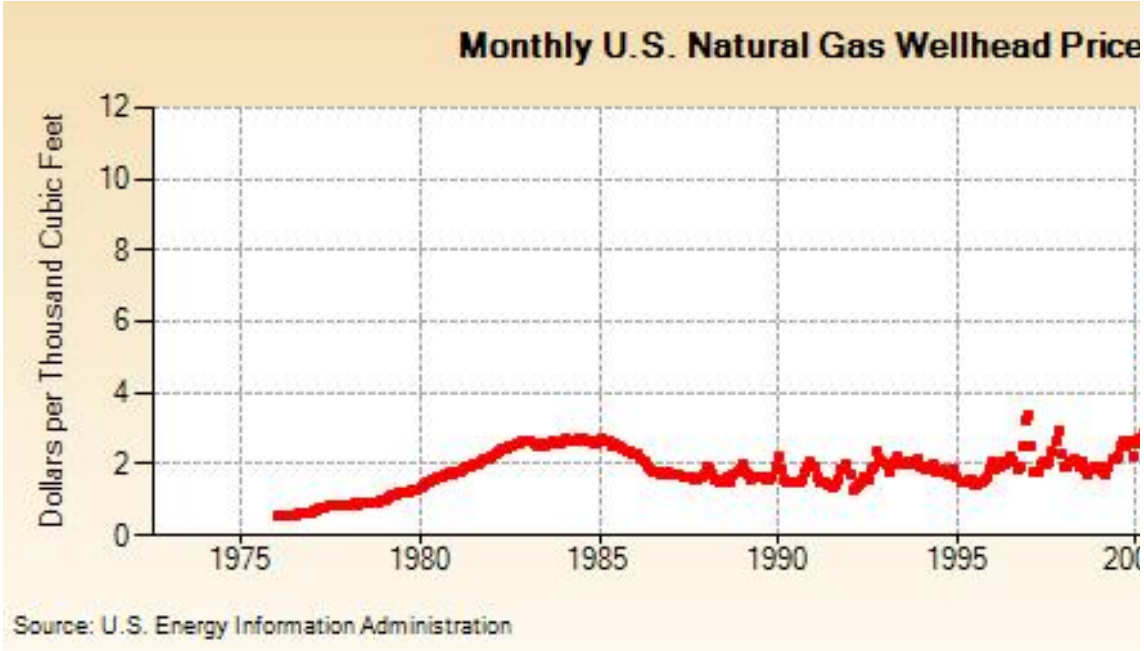
Philip Giudice, Commissioner, Massachusetts Department of Energy, I

5% of the generating capacity in Ma
is needed fewer than 88 hours pe

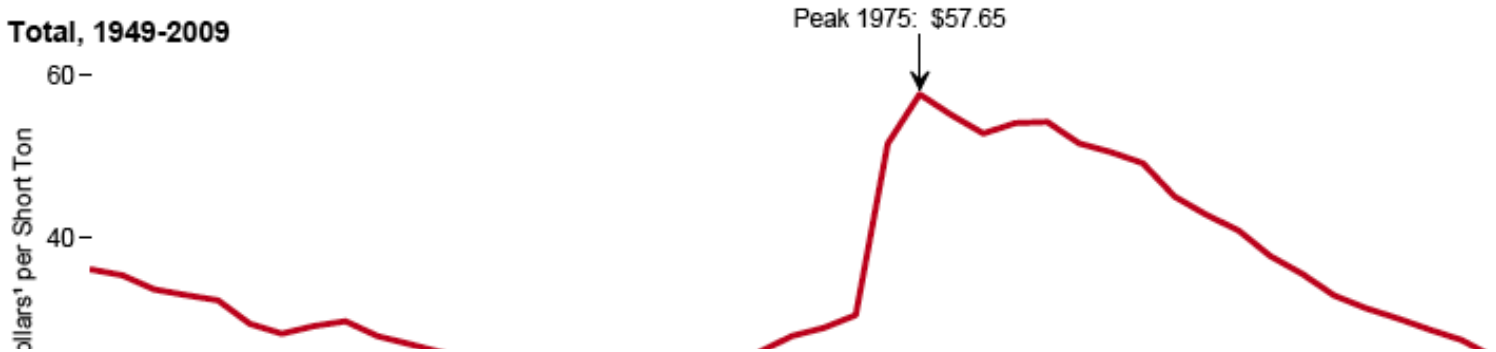
4

Rising prices

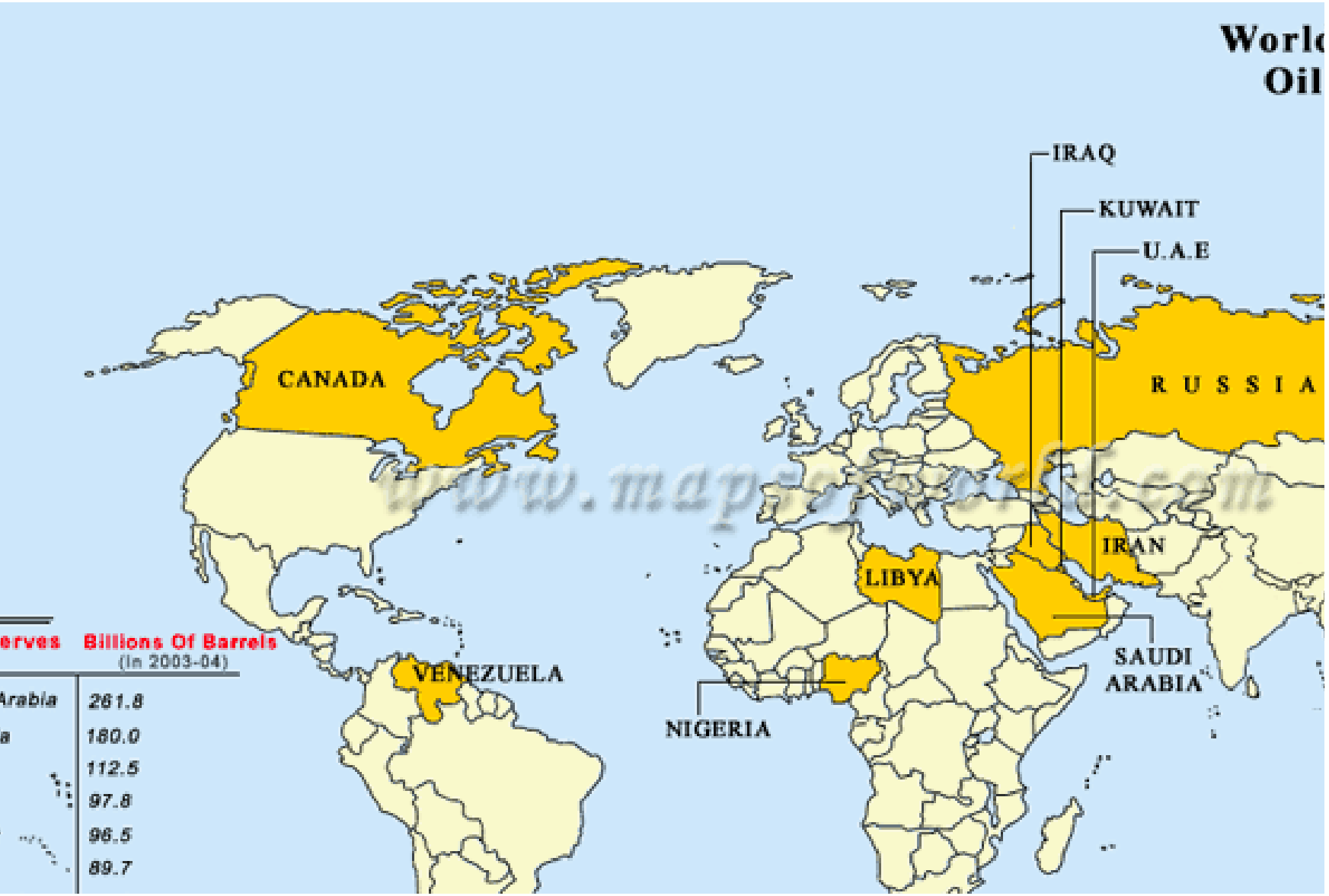
Gas Price
housan Cu. Ft.)



Prices
llars
9]



3 Energy securi

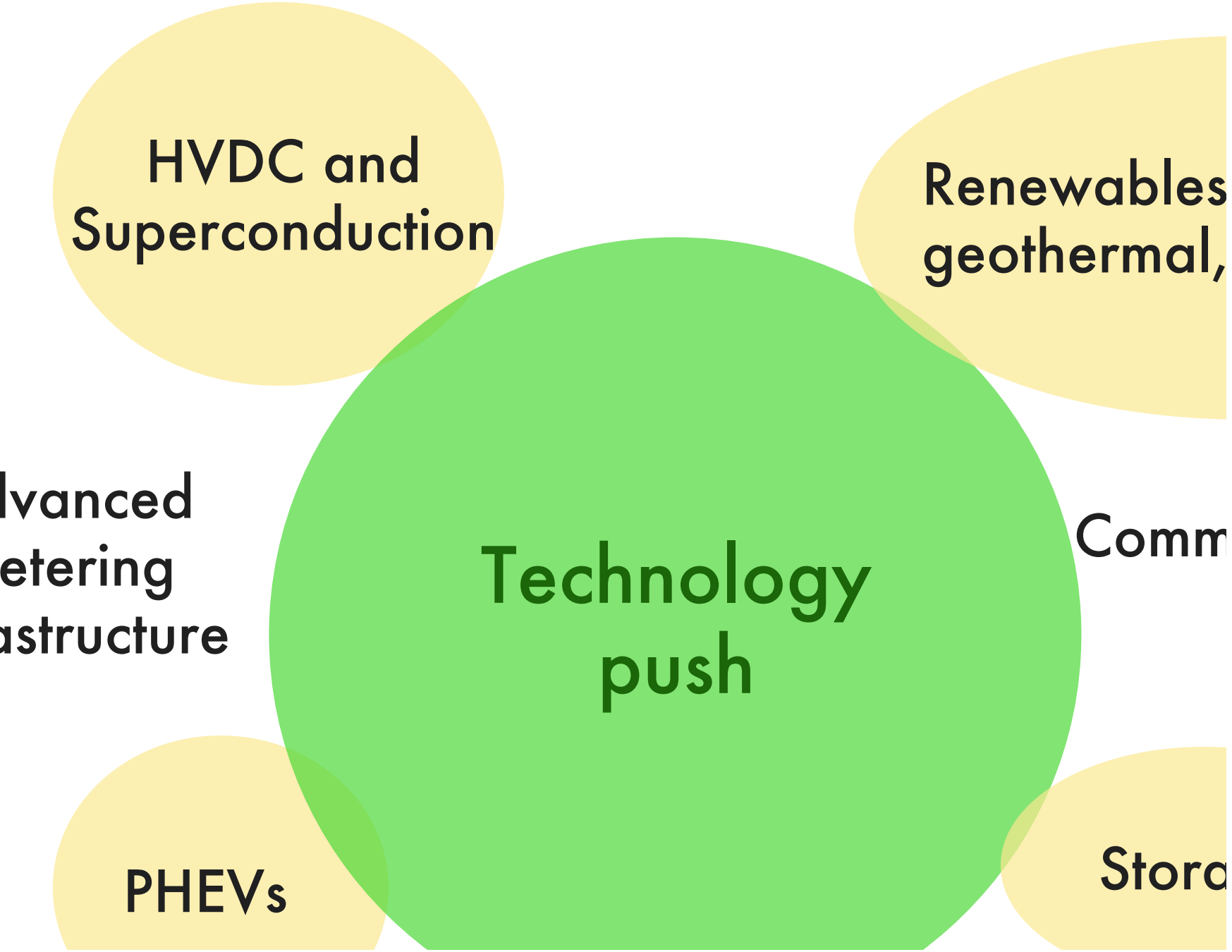


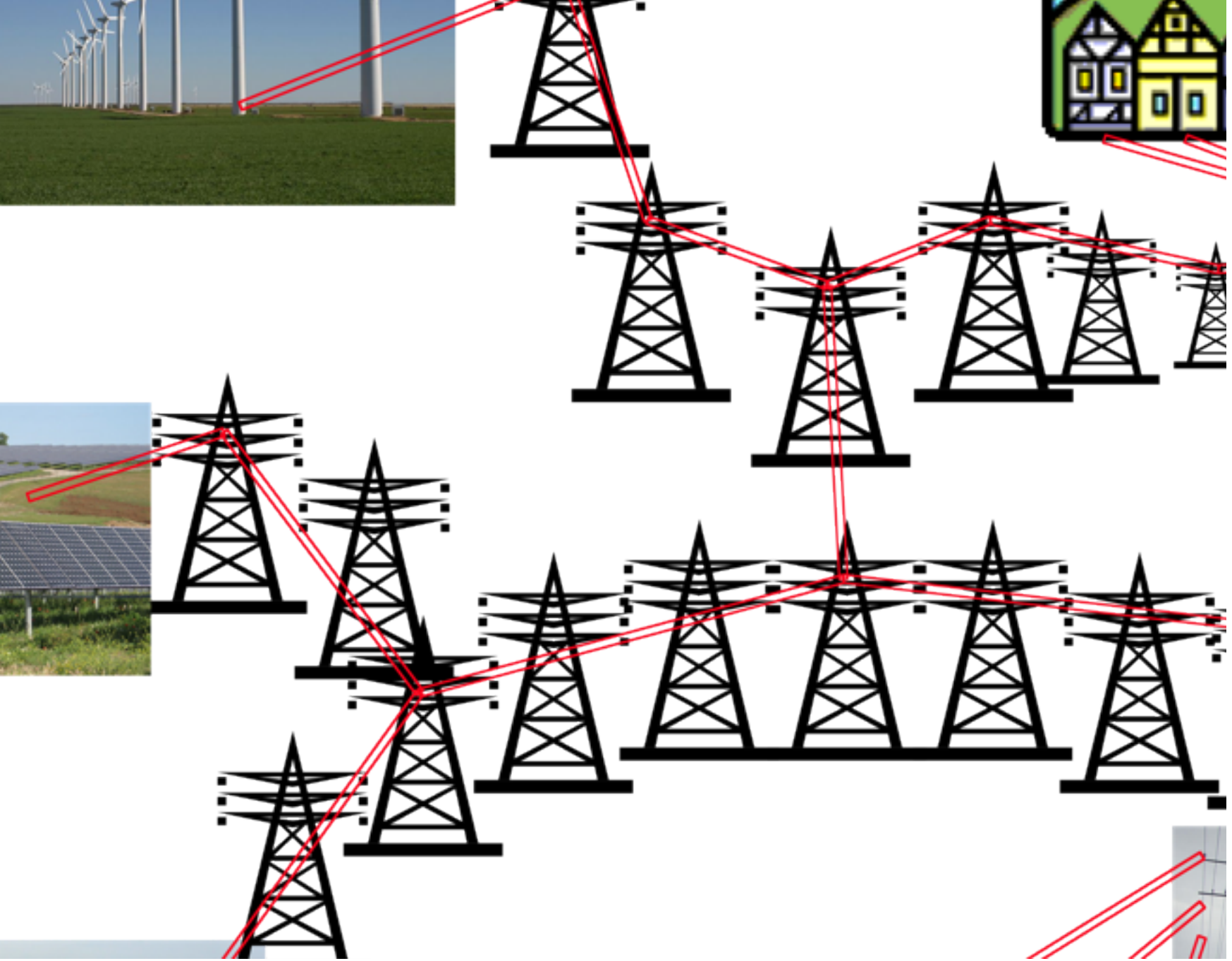
Casca
failu

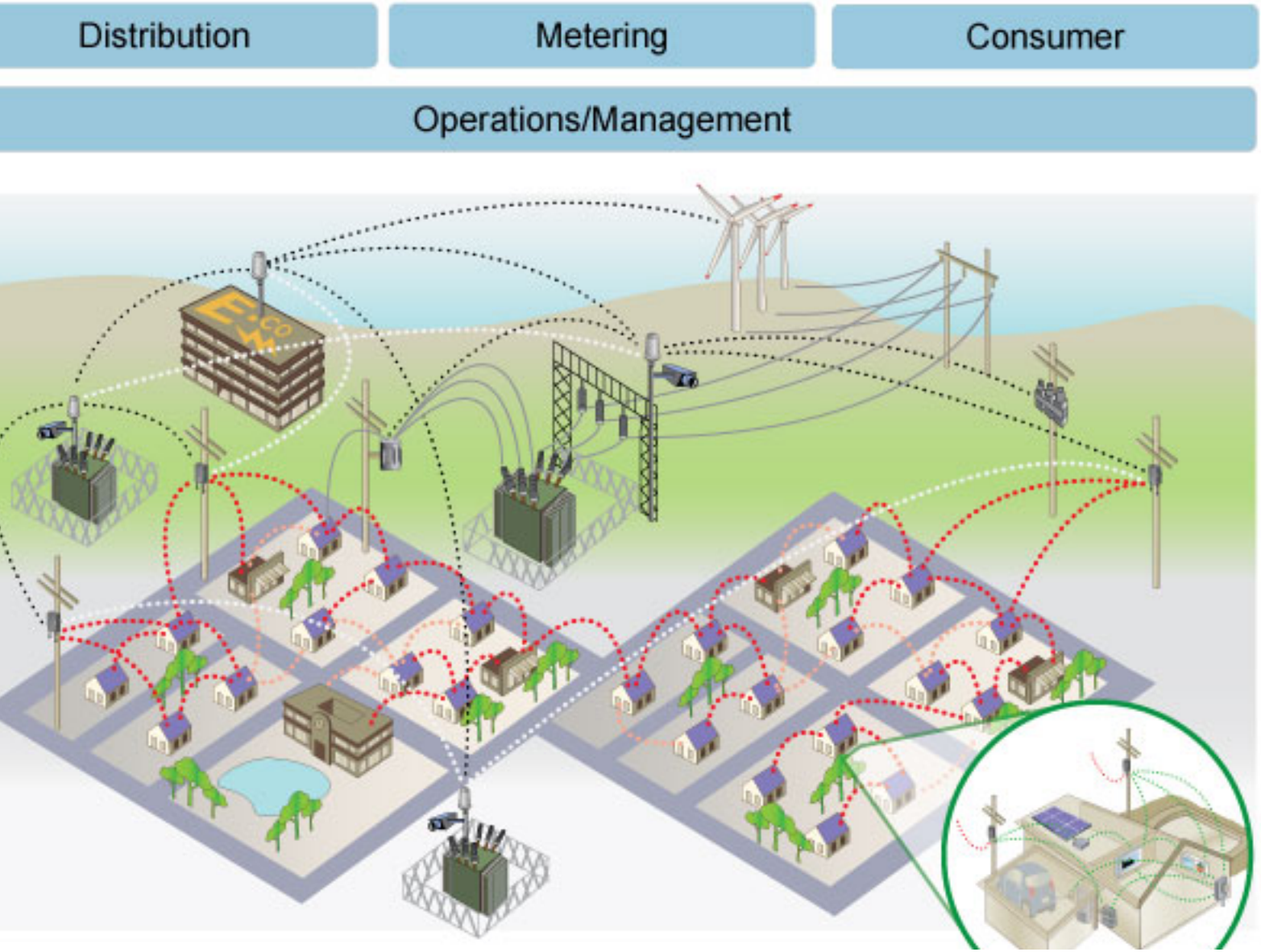
7 Generation ga

- **TWh generated (2008 est.)**
- US 4,110
- China 3,451
- India 723

- **MWh/ca (2008 est.**
- 13.25
- 2.58
- 0.61


HVDC and
Superconduction
Renewables
geothermal,
lvanced
etering
astructure
Technology
push
Comm
PHEVs
Stora



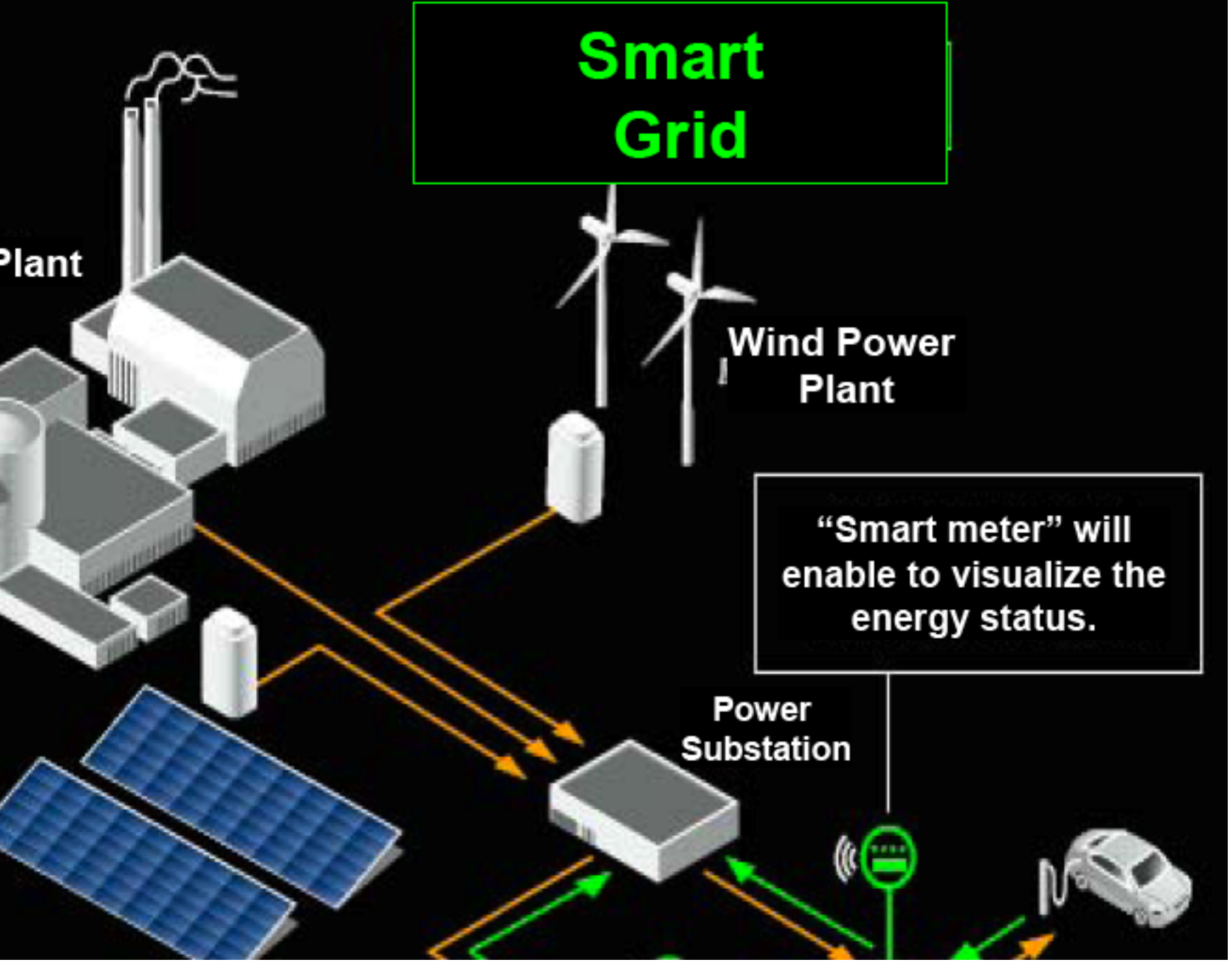


Head-E

Distribu
(Wide A

Meterin
(Neighb

Consun
(Home A


Smart
Grid
Plant
Wind Power
Plant
“Smart meter” will
enable to visualize the
energy status.
Power
Substation


The Smart Grid Can Deliver
Market
$
kW

Problems

Millions of sources

Stochastic sources

Backhauling RE

Two-way flows

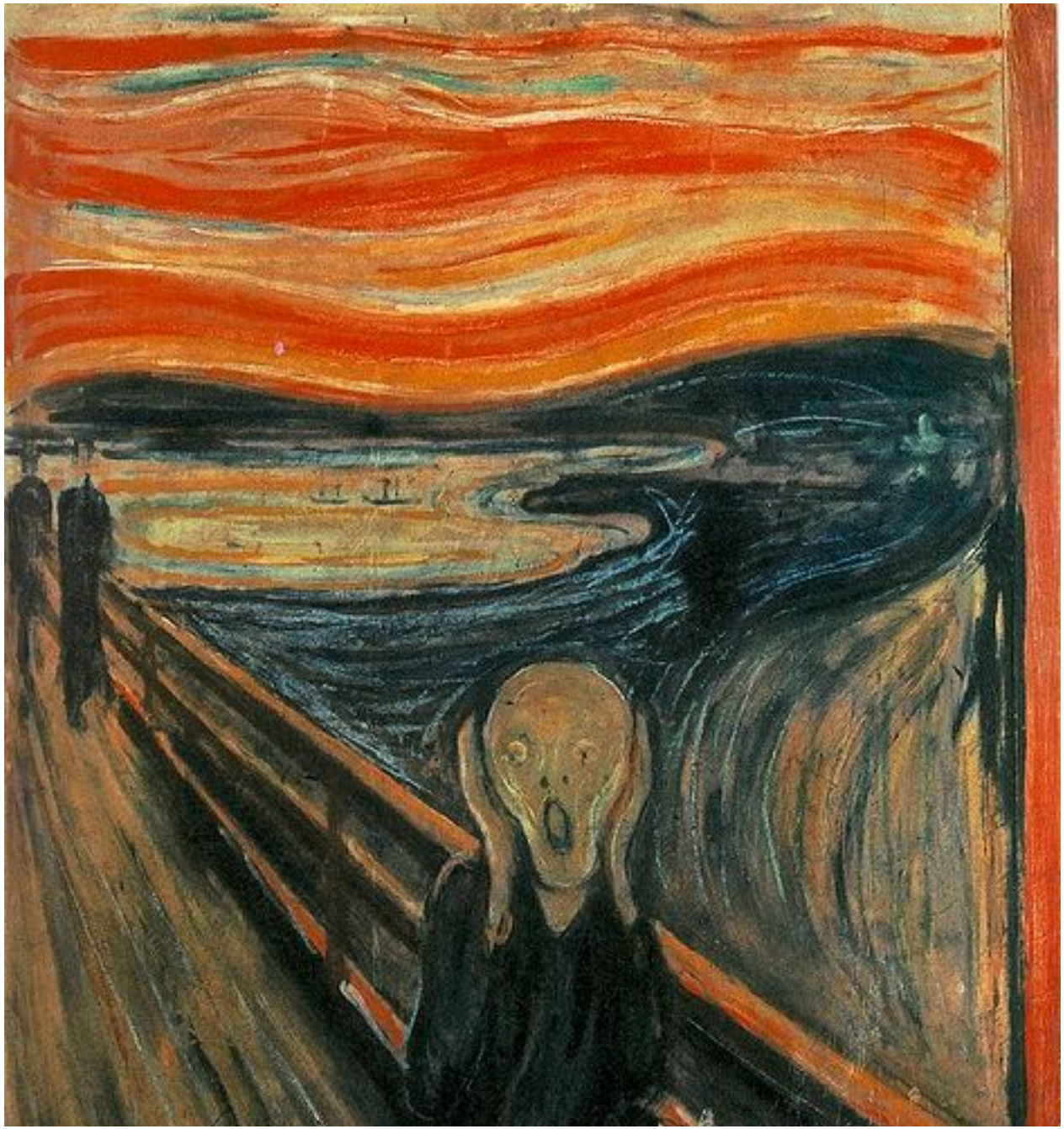
Non-traditional
utility players

- Incentivizatio
- Security
- Dealing with s
- Variable dema
- Legacy compa

In a nutshell

A relatively static, predictable, stable system with inelastic loads and a few points of control

A highly dynam unpredictable potentially ur system with e loads and mil points of cont



Its not enough to

- Reduce electricity use
- Use Internet as a communicatio
  overlay

Hypothesis

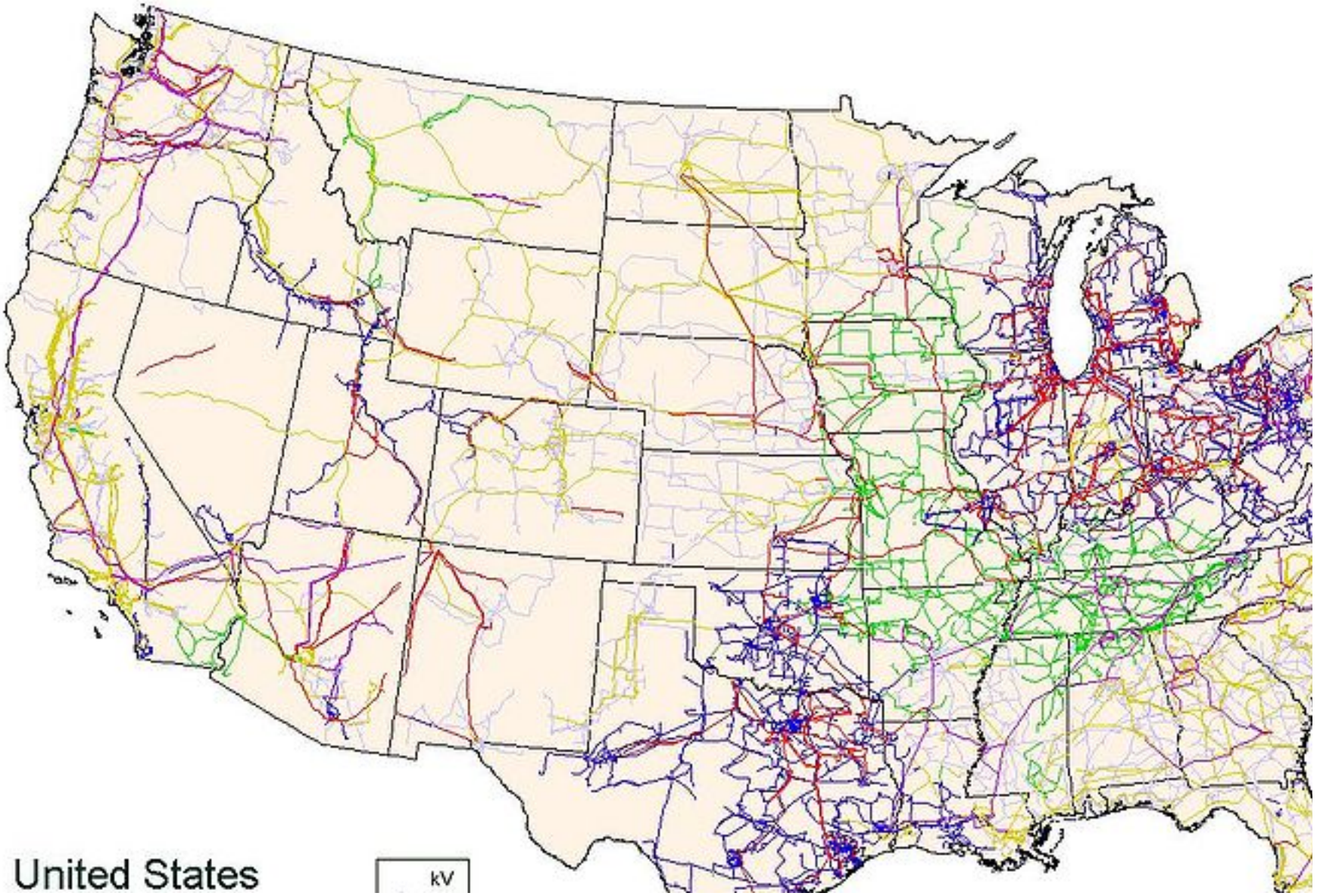
- Internet **concepts** can be used to the grid

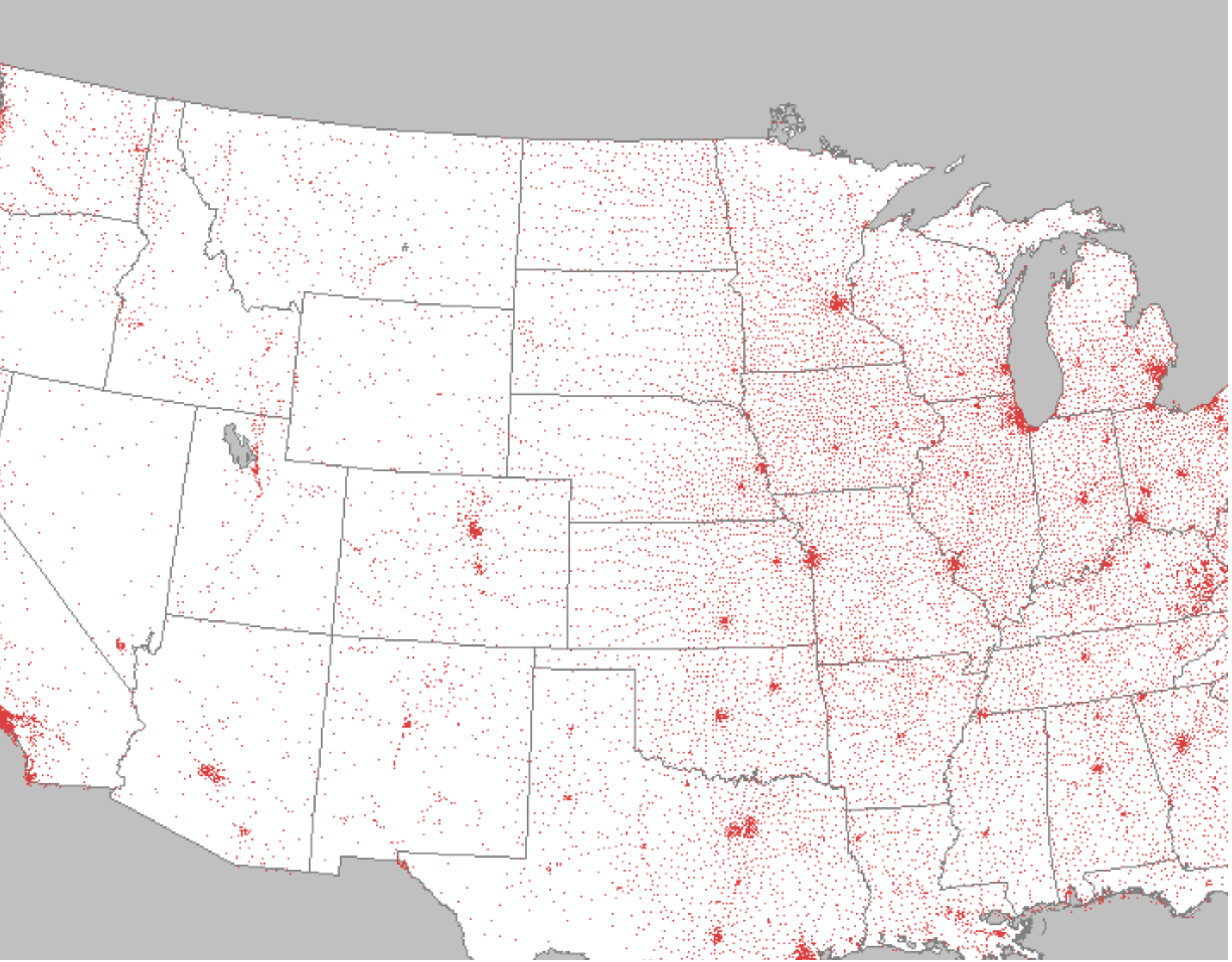
Similarities

- Vast
- Historically similar
  - bottom up + top down

Similarities

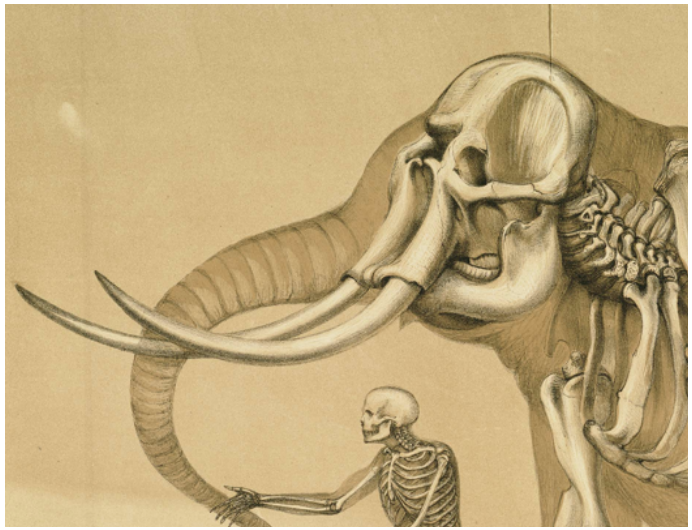
- Both match geographically distr
  demands with distributed gener


United States
kV



Similarities

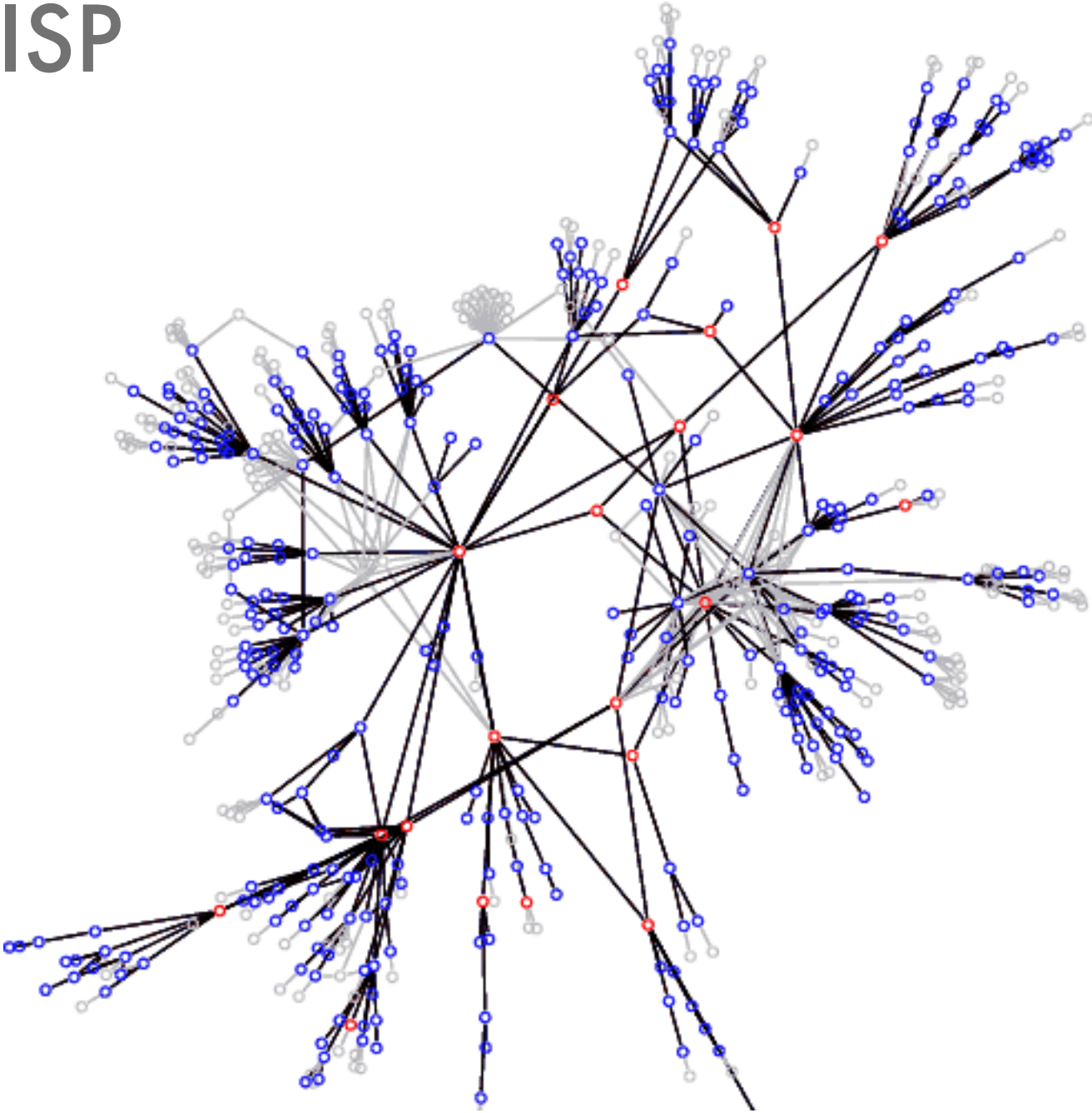
- Heterogeneous
- Critical to society
- **Ossified**

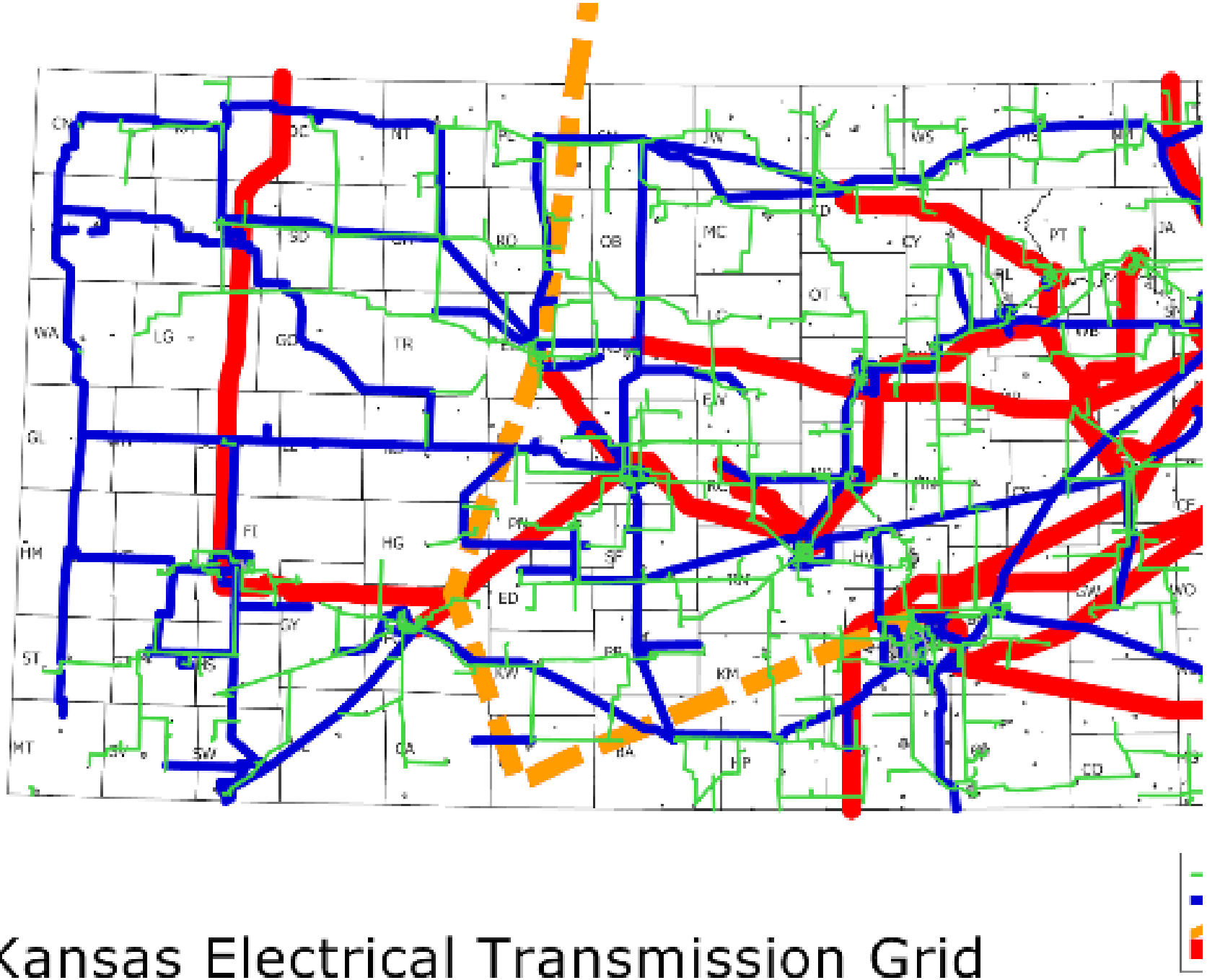


Similarities

- Hierarchical
  - mesh-like core designed for hi capacity
  - tree-like access network

mid-size ISP

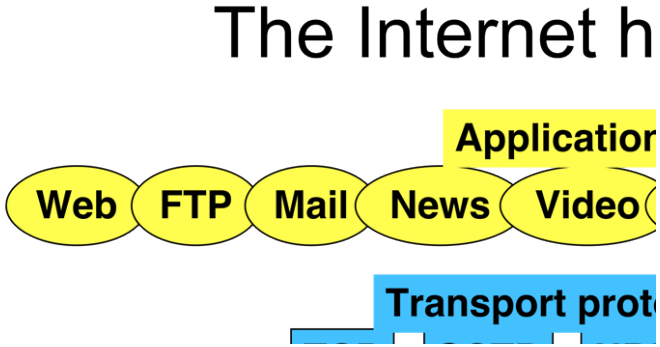




Kansas Electrical Transmission Grid

Similarities

- Simple API

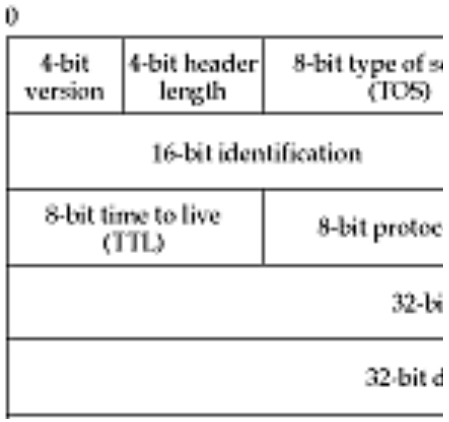


Similarities

- Balance **centralization** *Tier 1 ISP,*
  - long-haul transmission
  - generation = data centers
  - strict control
- and **decentralization** *Tier 2 ISP,*
  - aggregation

Differences

- Electricity has no **headers**
  - no type
  - no destination



Differences

- Primarily one-way vs. primarily way flows

Differences

- Long-haul upgradability
  - fiber optic link vs. cables

Differences

- Grid has practically no storage
  - Batteries not quite the same as DRAM!
  - $500/KWh

Research topics.

1. Stochastic mode

- Insight
- {Solar, Wind} = VER sources
- Electrical loads = -(VER sources)
- Can renewable energy be made r
- Under what conditions is

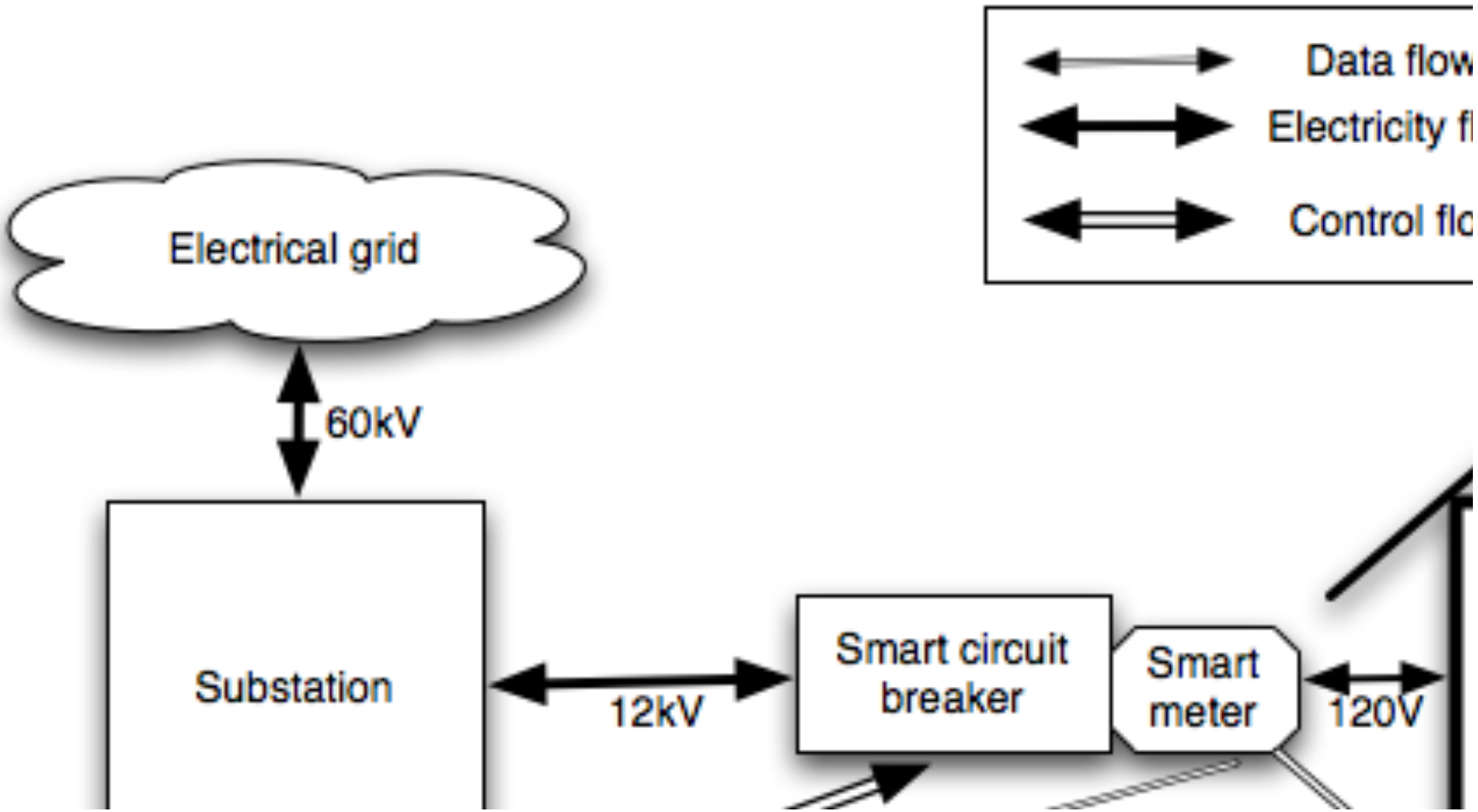
2. PHEV = DIN

- Use ‘data mules’ to carry energy

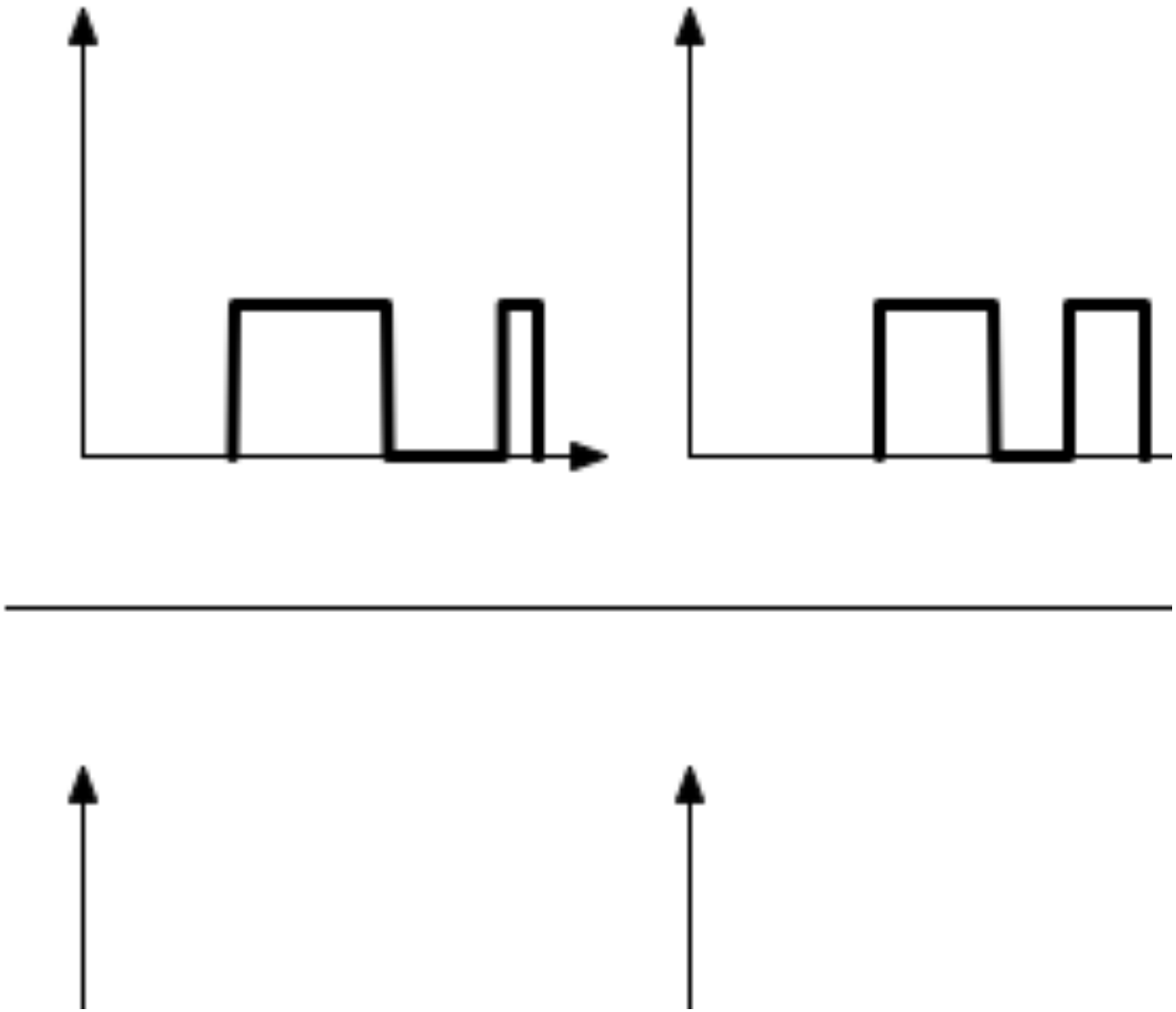
3. Load contro

- Circuit breaker = peak-rate limite
- Frequency droop = network cong
- Can we use proactive and reactiv congestion control?

Architecture



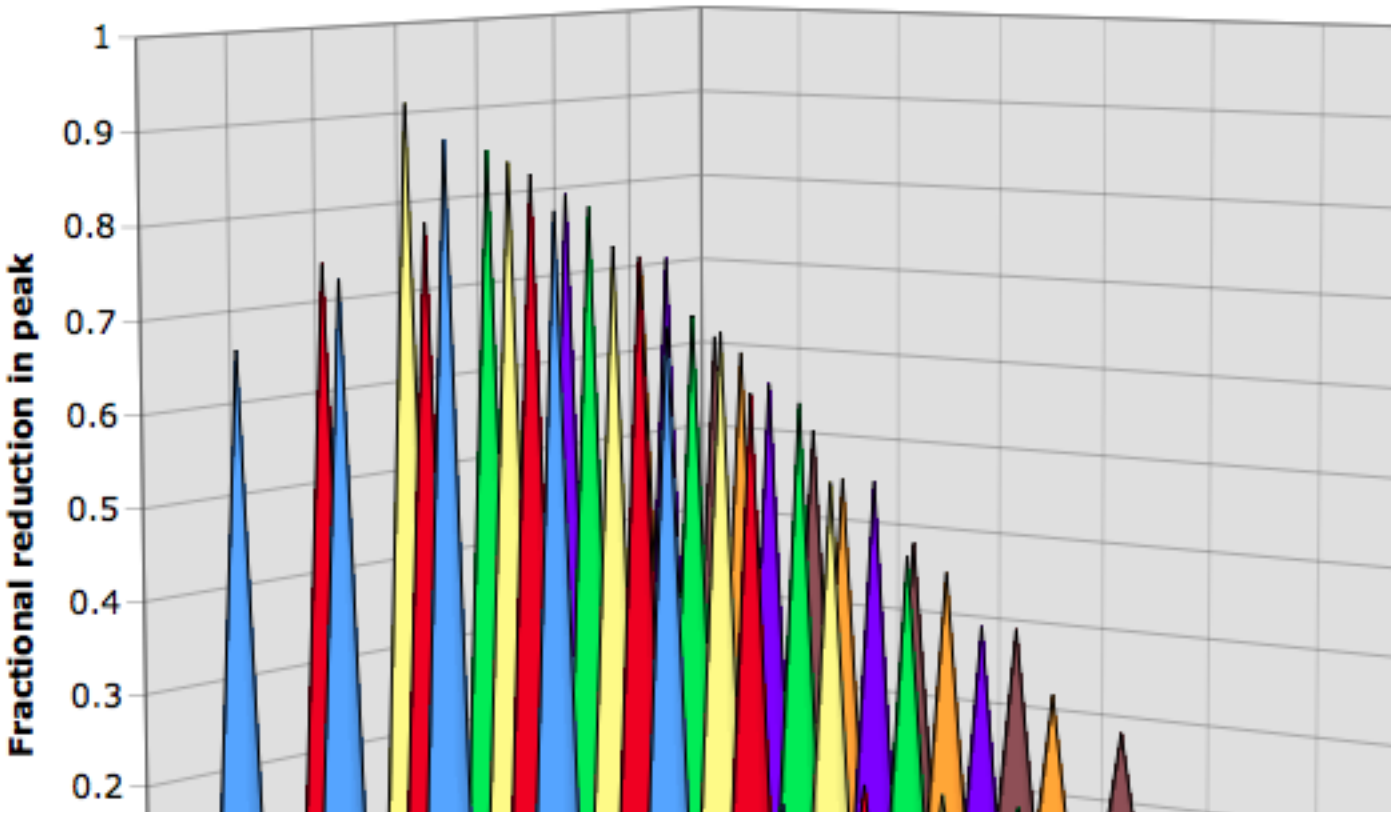
Proactive contro



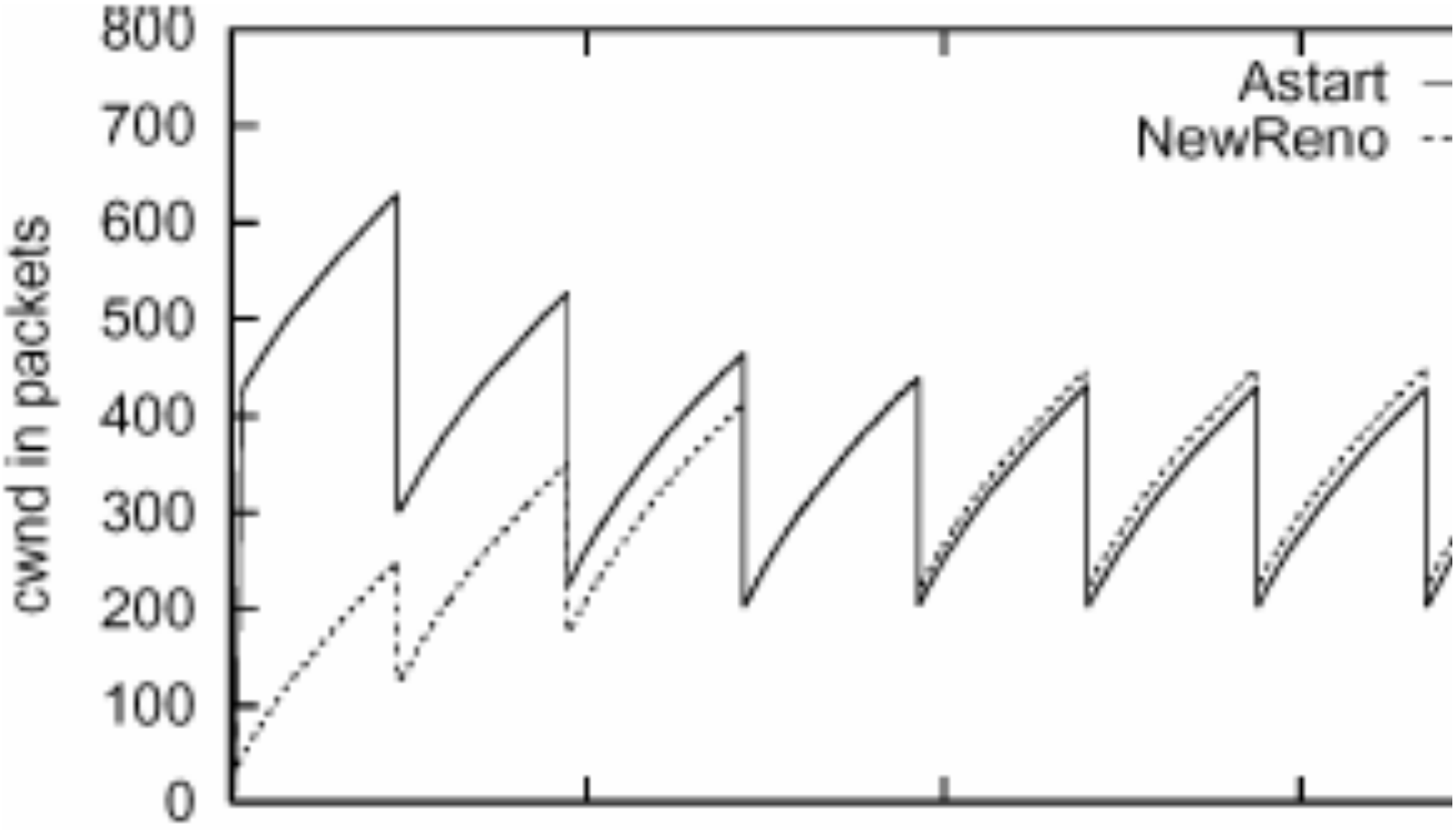
How well does it w

- Assume homogeneity
- Uncorrelated can be modeled as Binomial
- Correlated is deterministic

% Reduction in pe



Reactive contro



Many open probl

- How to monitor and predict the load at a home?
- What if there is a plugin electric car in the house? A
- What is a fair policy for load reduction? Can it lead
- What if the load profile is violated?
- What is the best reactive policy?
- How to compute heterogeneous schedules?
- What do loads look like in real life?

Conclusions

- 2010-2020 will decide the grid of
- Internet ~= Grid
- 40 years of Internet research {co
  should, may} help
- Rich area for impactful research

tp://blizzard.cs.uwaterloo.

Overview paper in ACM Sigcomm G
Net Workshop, August 2010