Waterloo Institute for Sustainable Energy

# Paths to a Sustainable Energy Future

## Energy- Environment- Economy

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First Summer School,
Lisbon, Portugal
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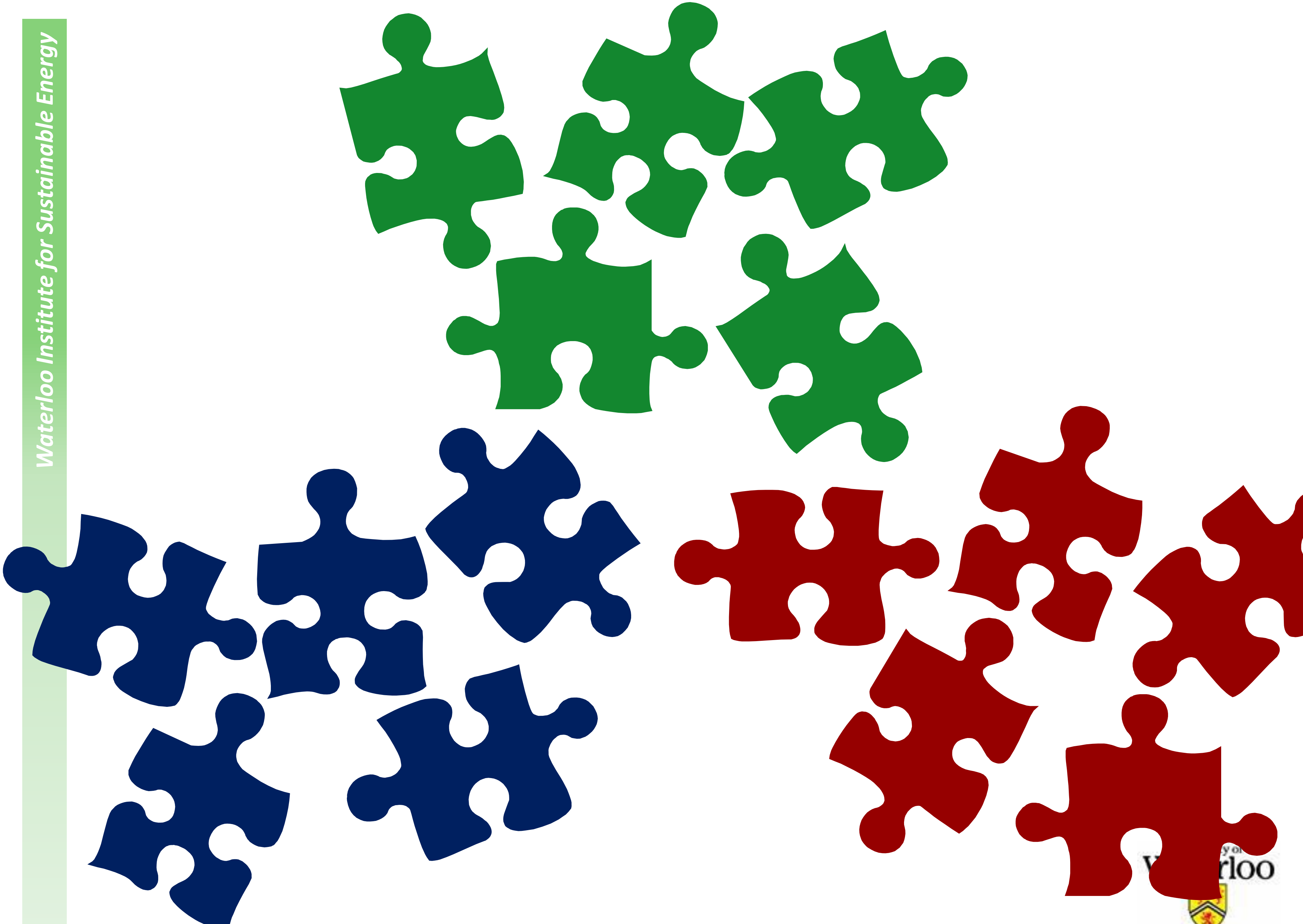

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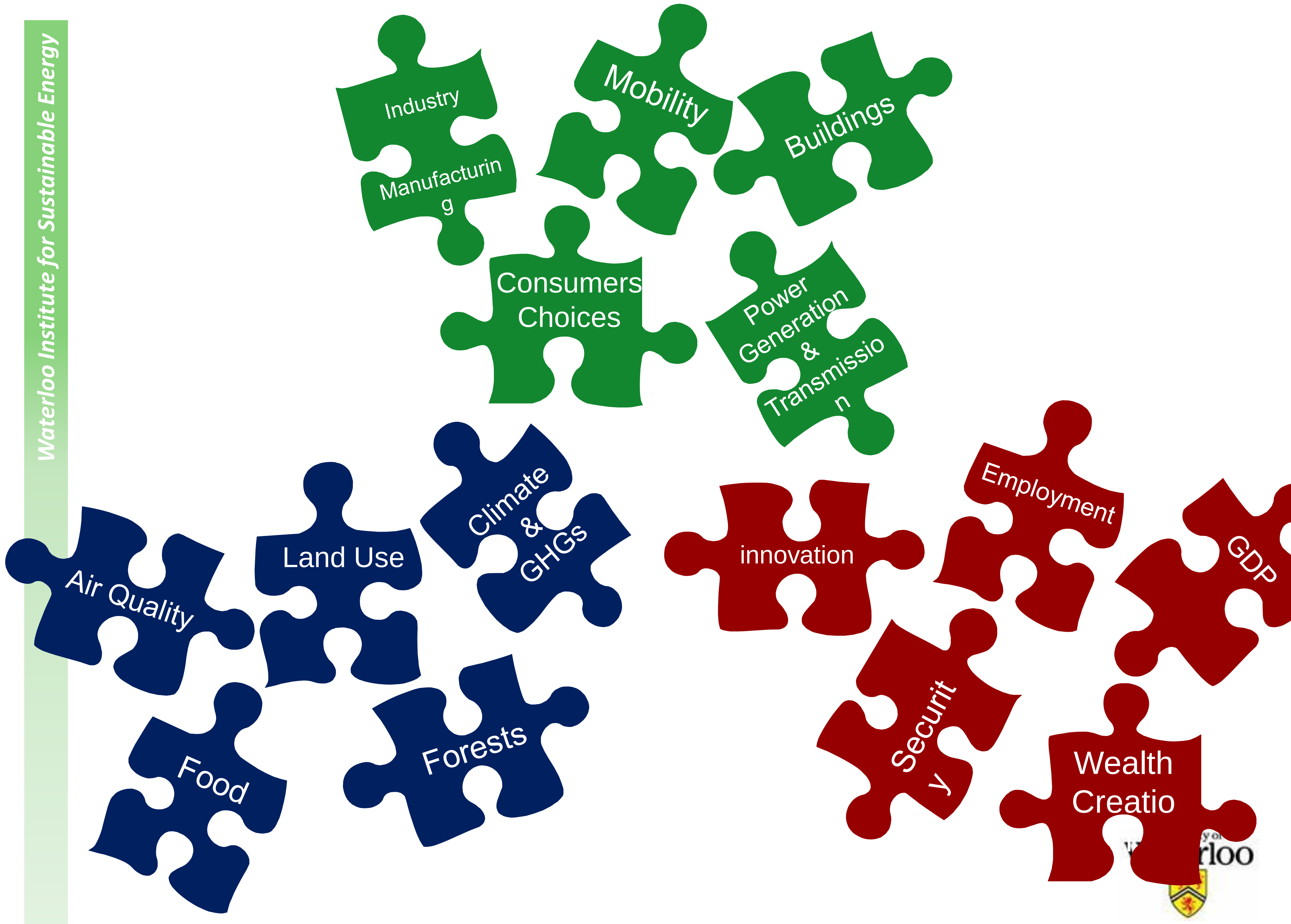

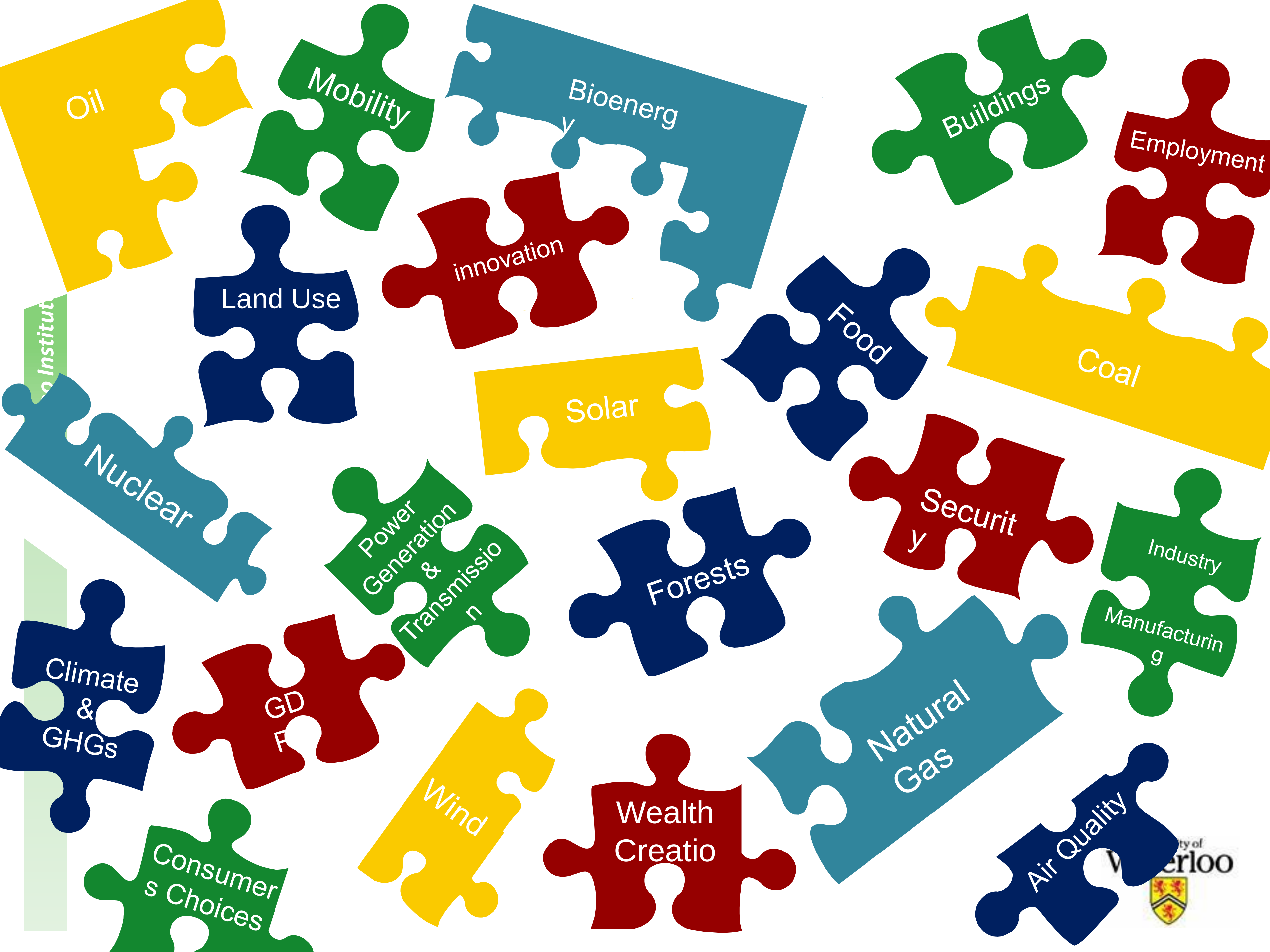
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Industry
Manufacturin g
Climate & GHGs
GD P
Natural Gas
Wind
Wealth Creatio
Air Quality
Consumer s Choices

# Today's Goals

- Global  Energy Trends & Global Challenges
- What this may mean for us?
  - Offer fresh thinking
  - Identify key issues, risks and uncertainties
  - Provide a rationale for innovation and some credible – "hopeful" paths for the future
- @Waterloo: our contribution to solutions
- Bring coherence to a complex problem
  - a "witches brew of policies, politics and promise of technology innovation"

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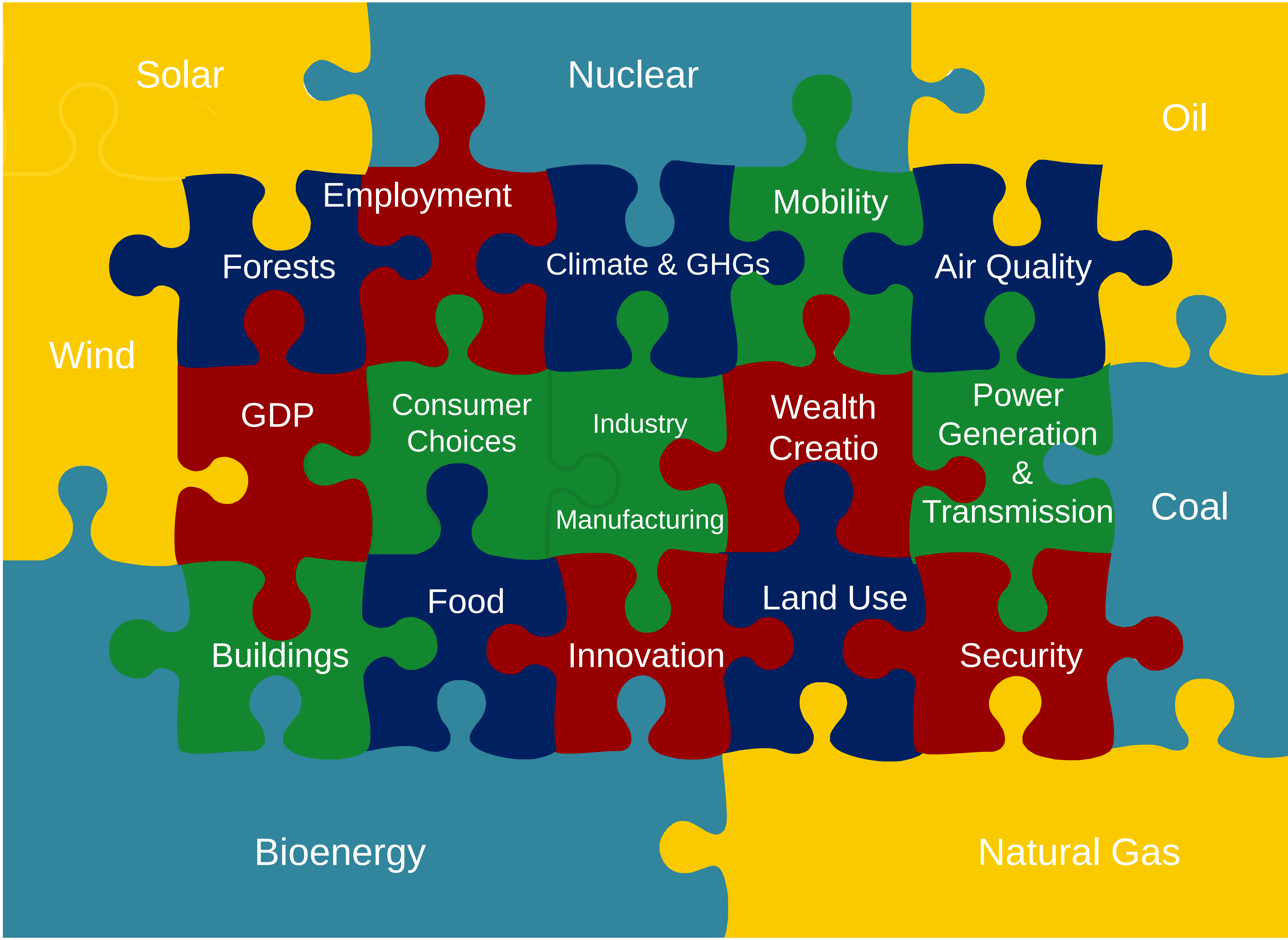
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Power Generation & Transmission
Coal
Food
Land Use
Buildings
Innovation
Security
Bioenergy
Natural Gas

# World at Night

# Lack of Affordable Energy: What does it mean?


**Energy's link to human development:**

- **Productivity**
- **National Income**
- **Health**
- **Education**
- **Social Development**



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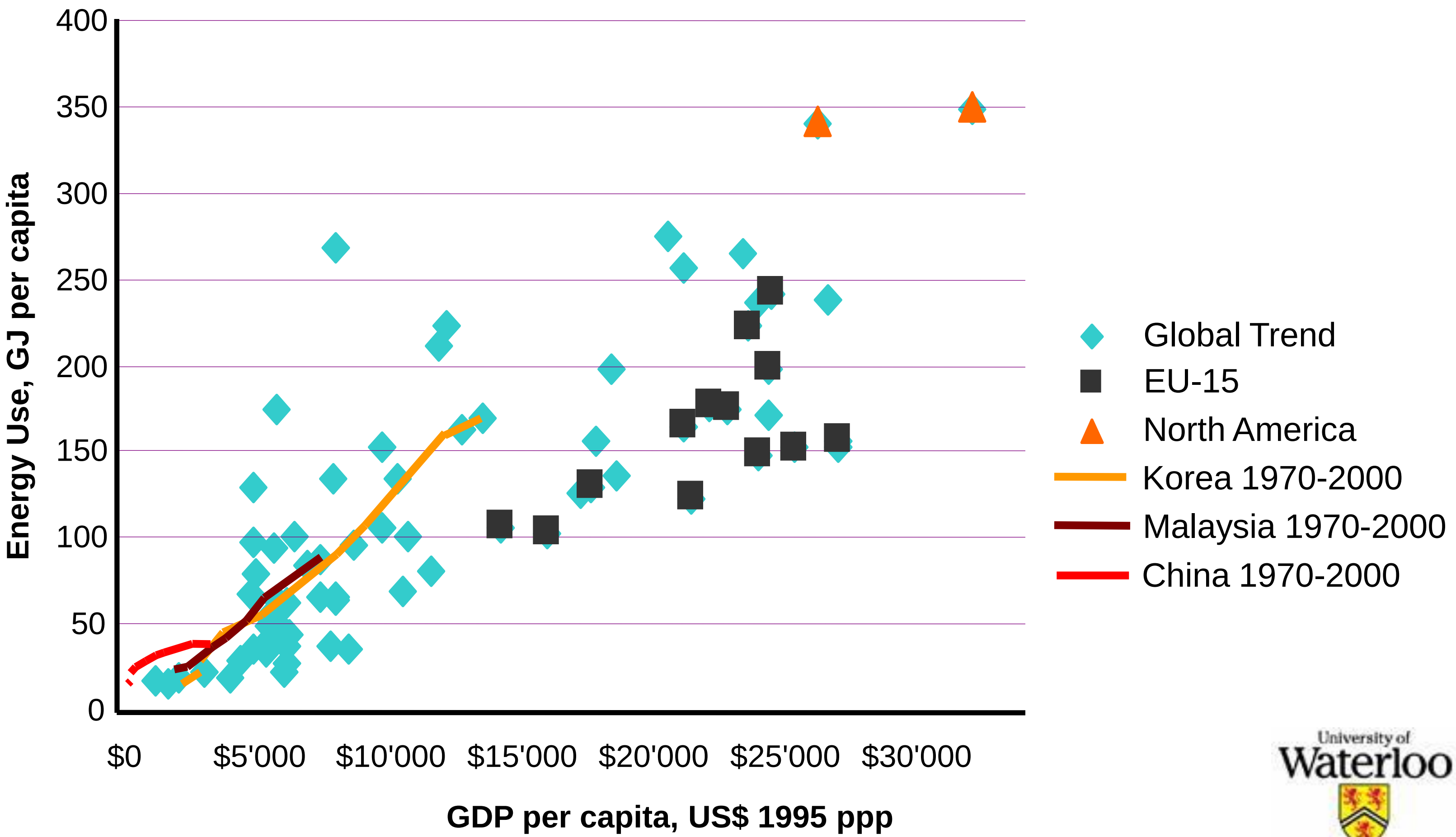
# Growth, development and energy demand

Basic premise – energy use and growth are strongly linked




Source: WBCSD adaptation of IEA 2003

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# Energy's Link to Life Quality

**Enhanced Well Being**
Life Expectancy: 80 yrs

$10^4$

**IMPROVED LIFE QUALITY**
Life Expectancy: 60 yrs

$10^3$

**BASIC QUALITY OF LIFE**
Life Expectancy: 60 yrs

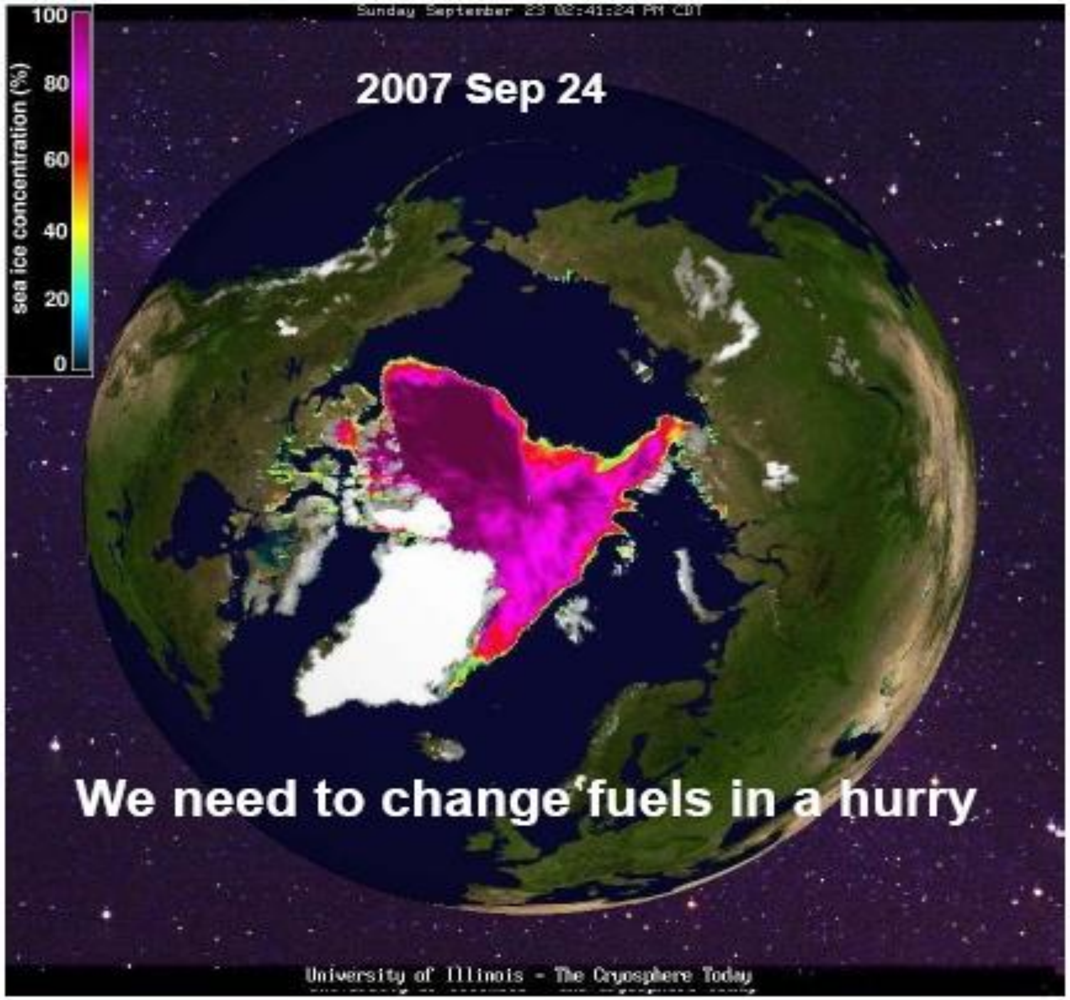
$10^2$

**SURVIVAL**
Life Expectancy: 40 yrs

Annual
$GDP/Capita

Annual
kWh/capita

# The global challenge: how to de-carbonize



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# Population Growth, Energy, Income

**Global population divided into income groups:**

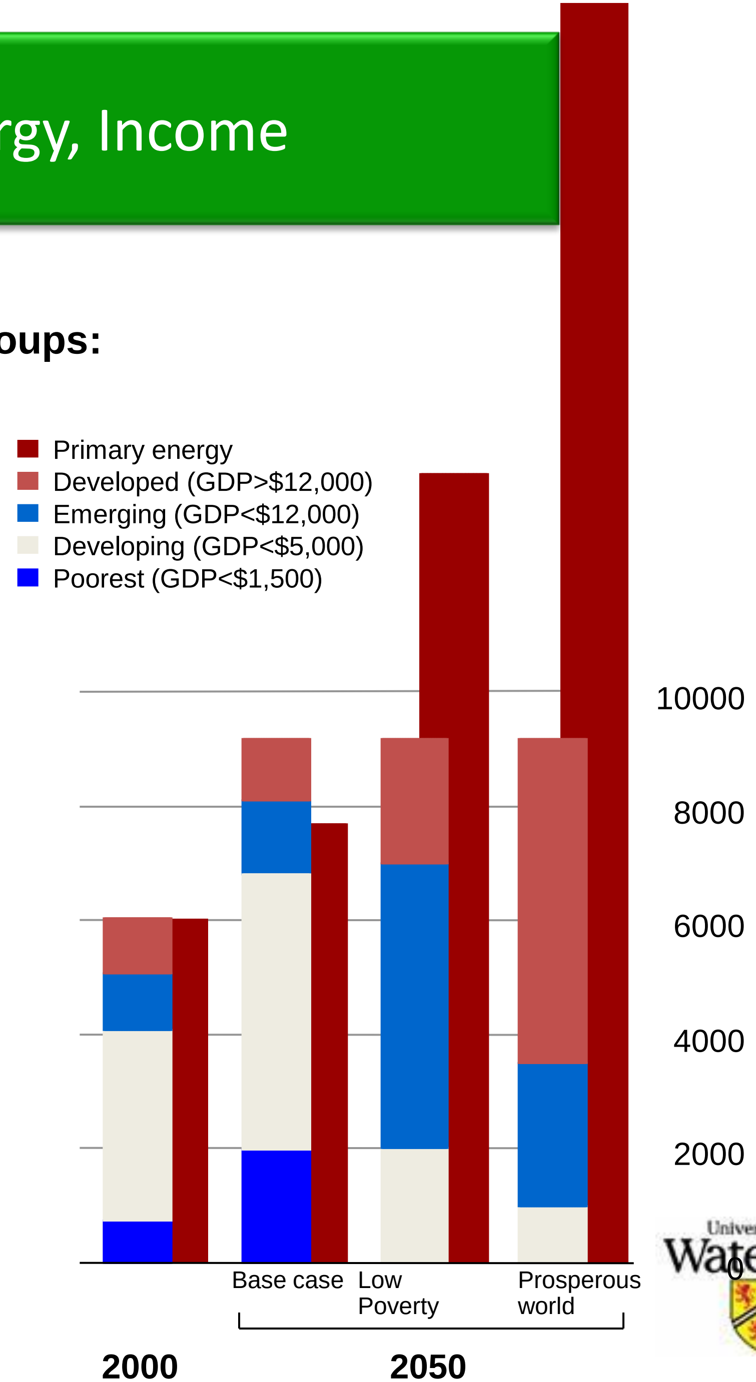
- **Poorest (GDP < $1,500)**
- **Developing (GDP < $5,000)**
- **Emerging (GDP < $12,000)**
- **Developed (GDP > $12,000)**

**Population expected to rise to 9 billion by 2050, mainly in poorest and developing countries.**

**Shifting the development profile to a “low poverty” world means energy needs double by 2050**

**Shifting the development profile further to a “developed” world means energy needs triple by 2050**

Source: WBCSD 2007




Source: WBCSD adaptation of IEA 2003

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# Meeting future energy needs (IPCC)

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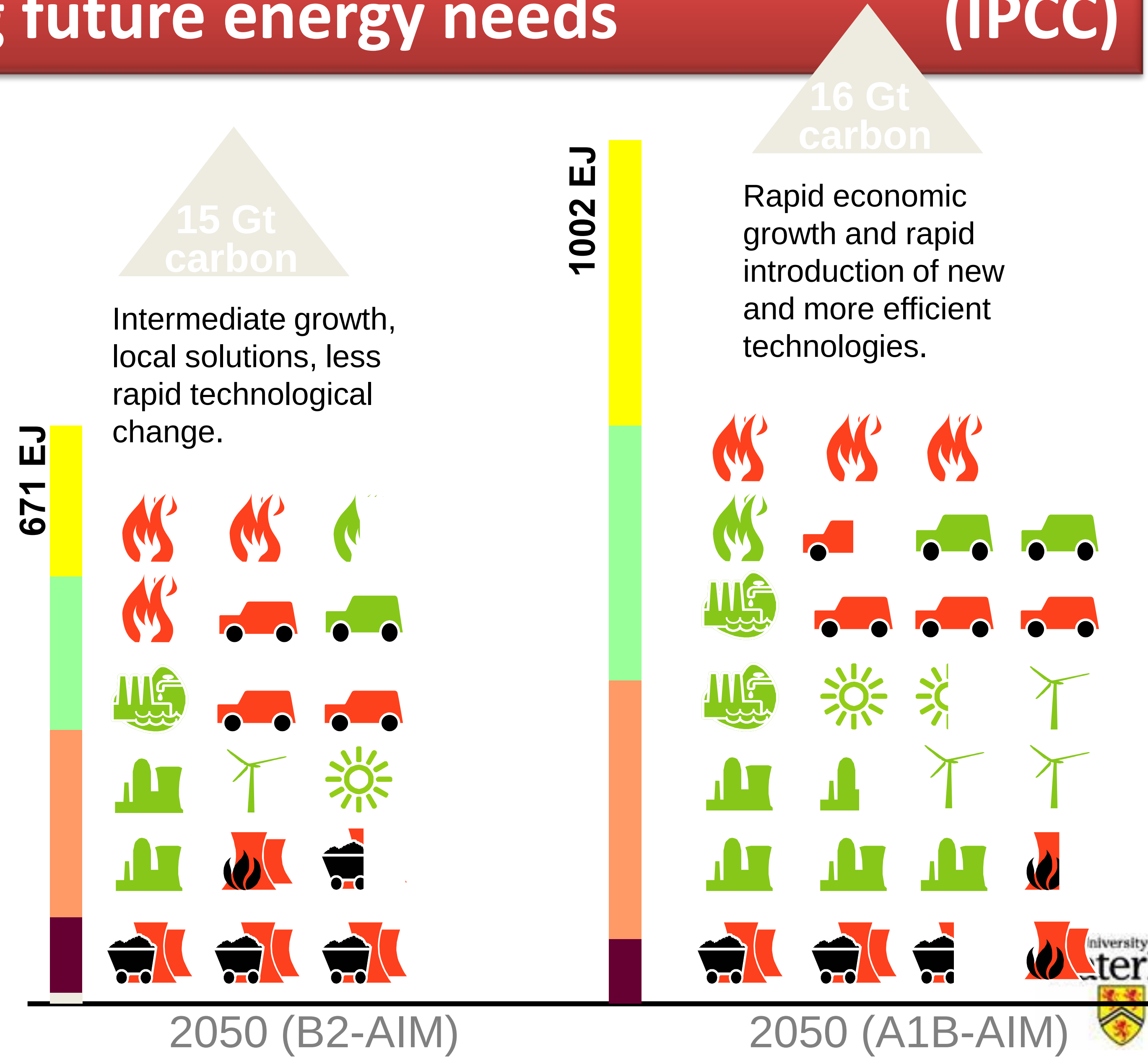
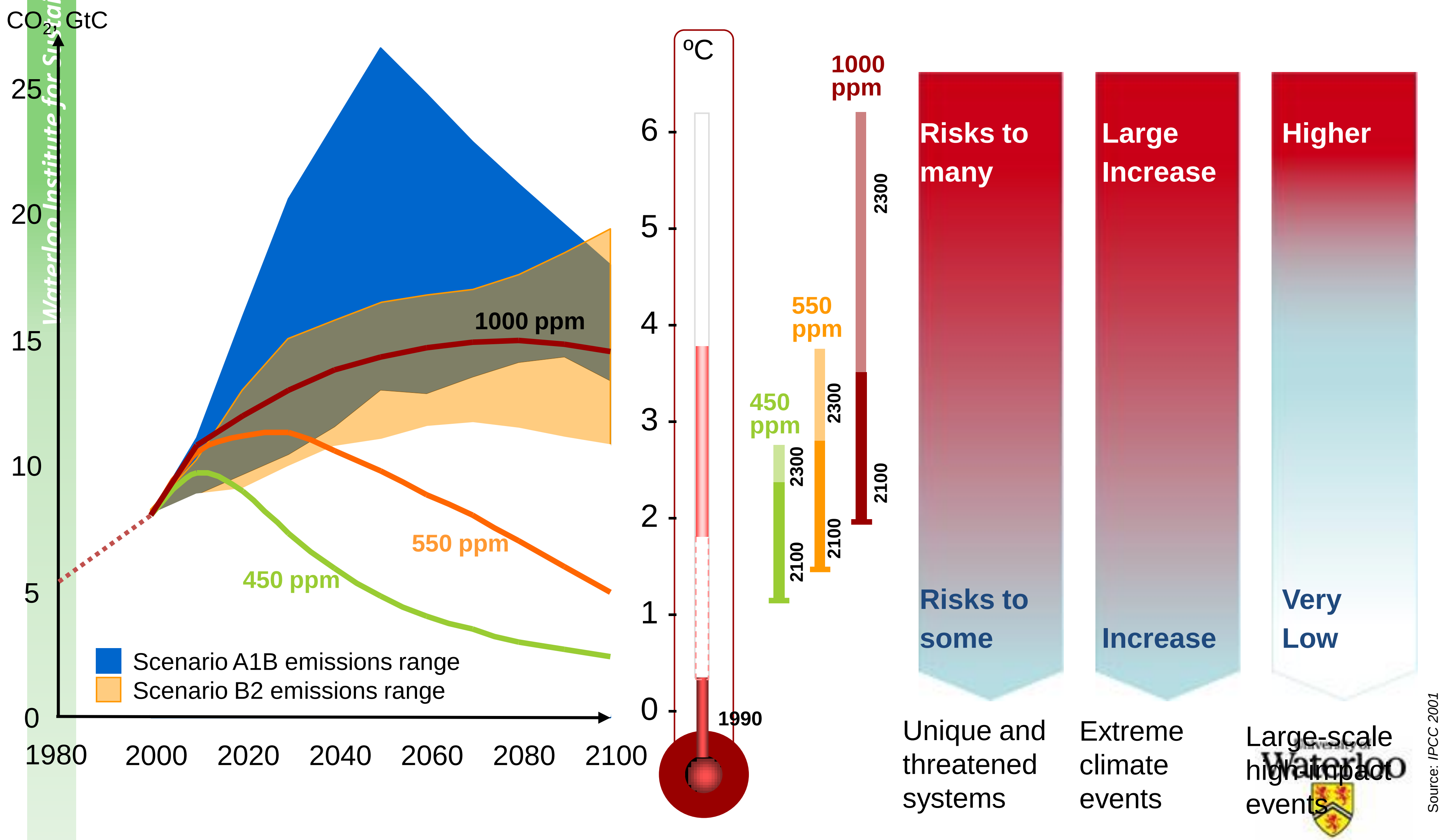
## Final Energy

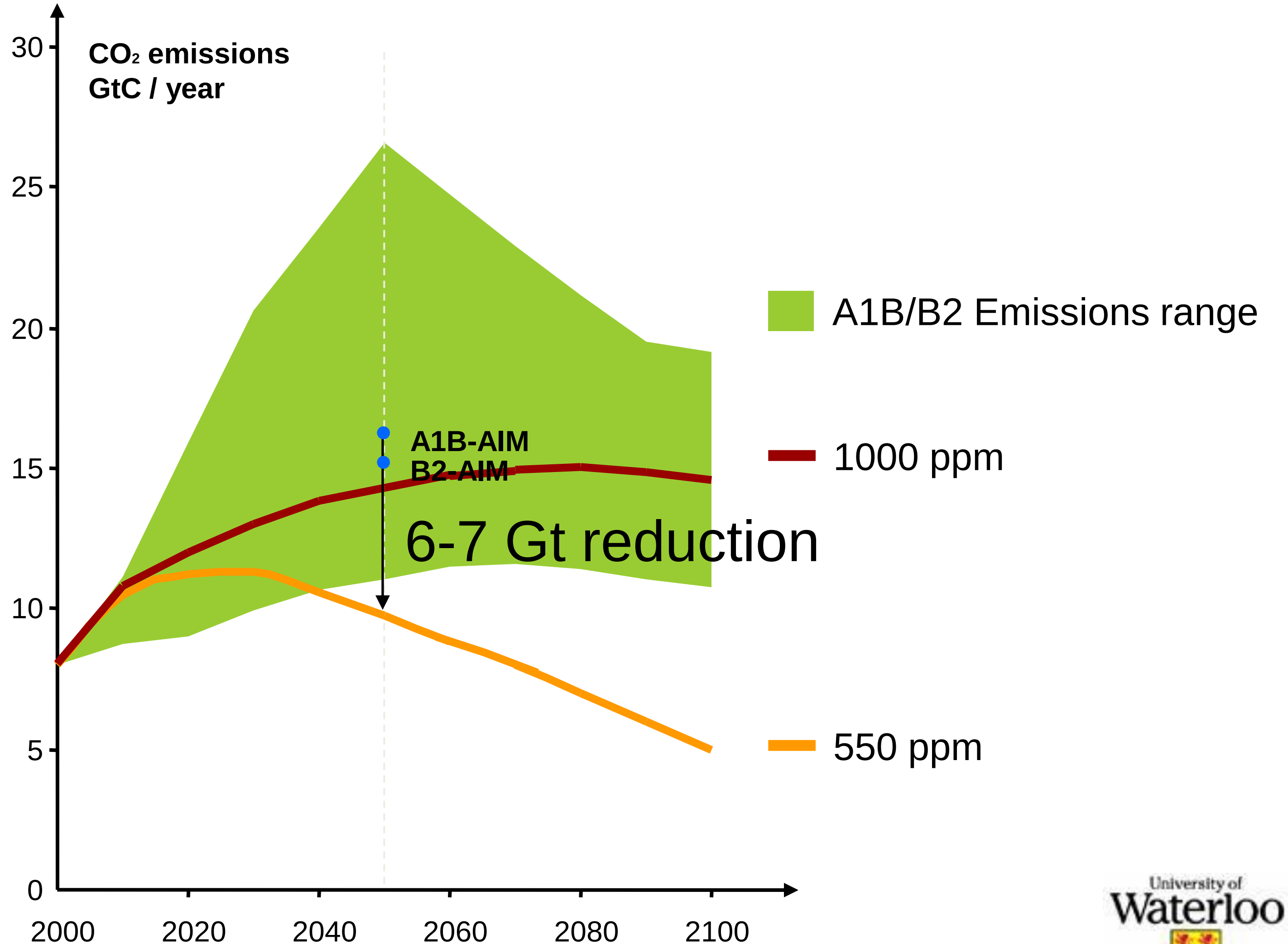
- Electricity
- Gas
- Liquids
- Solids
- Non-commercial



# Is there an acceptable limit for $CO_2$ emissions?



# Achieving a lower $CO_2$ stabilization




Source: IPCC 2000

**Energy sector will be driven towards a quantifiable, long term pathway for reduced GHG emissions**

if so

- ? **How do we get there**
- ? **What role for innovation**
- ? **What capacity for change**
- ? **What is the status of the infrastructure**
- ? **What are the governance and policy issues**

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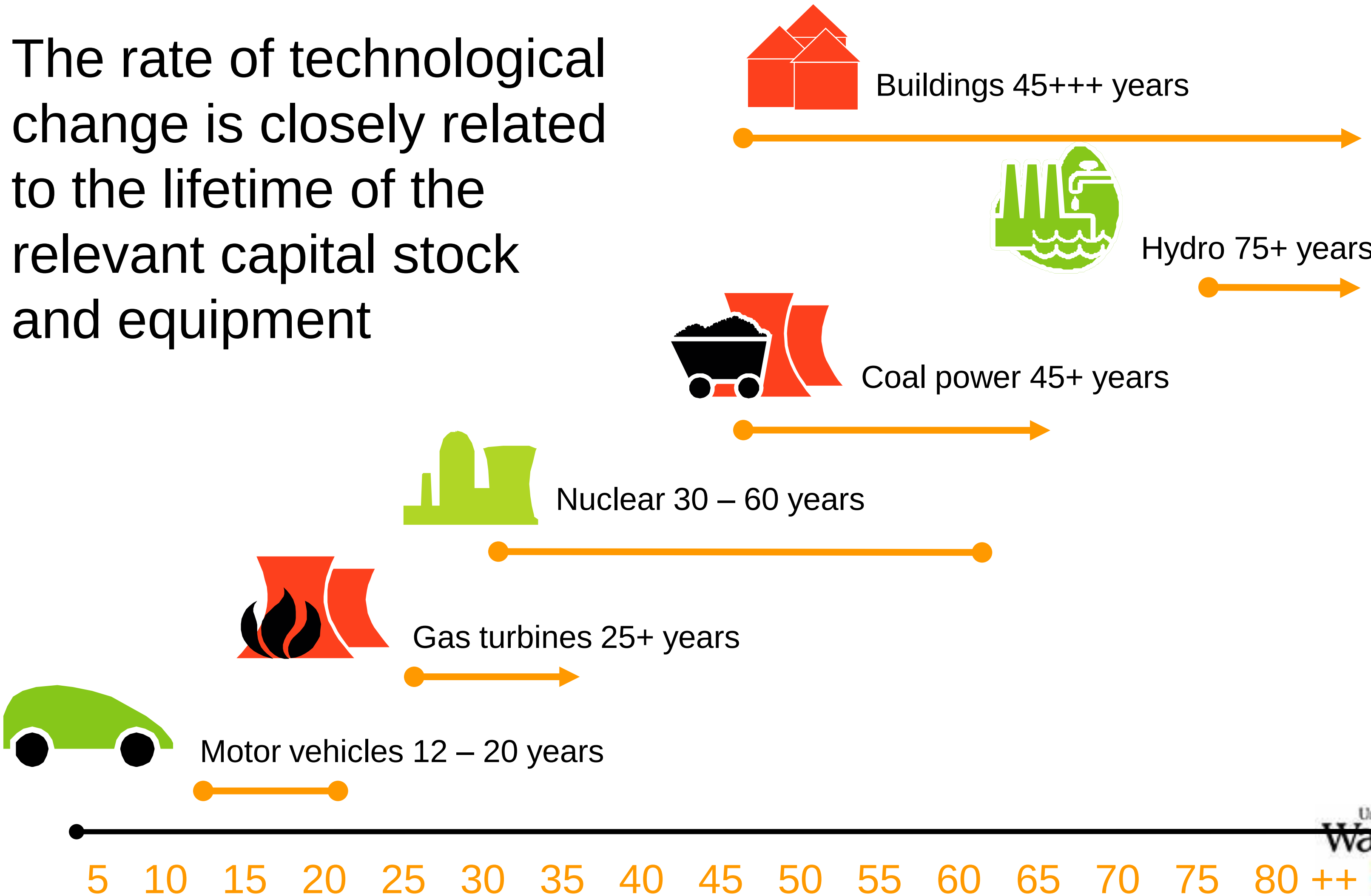
# The lifetime of energy infrastructure

The rate of technological change is closely related to the lifetime of the relevant capital stock and equipment




Source: WBCSD 2007

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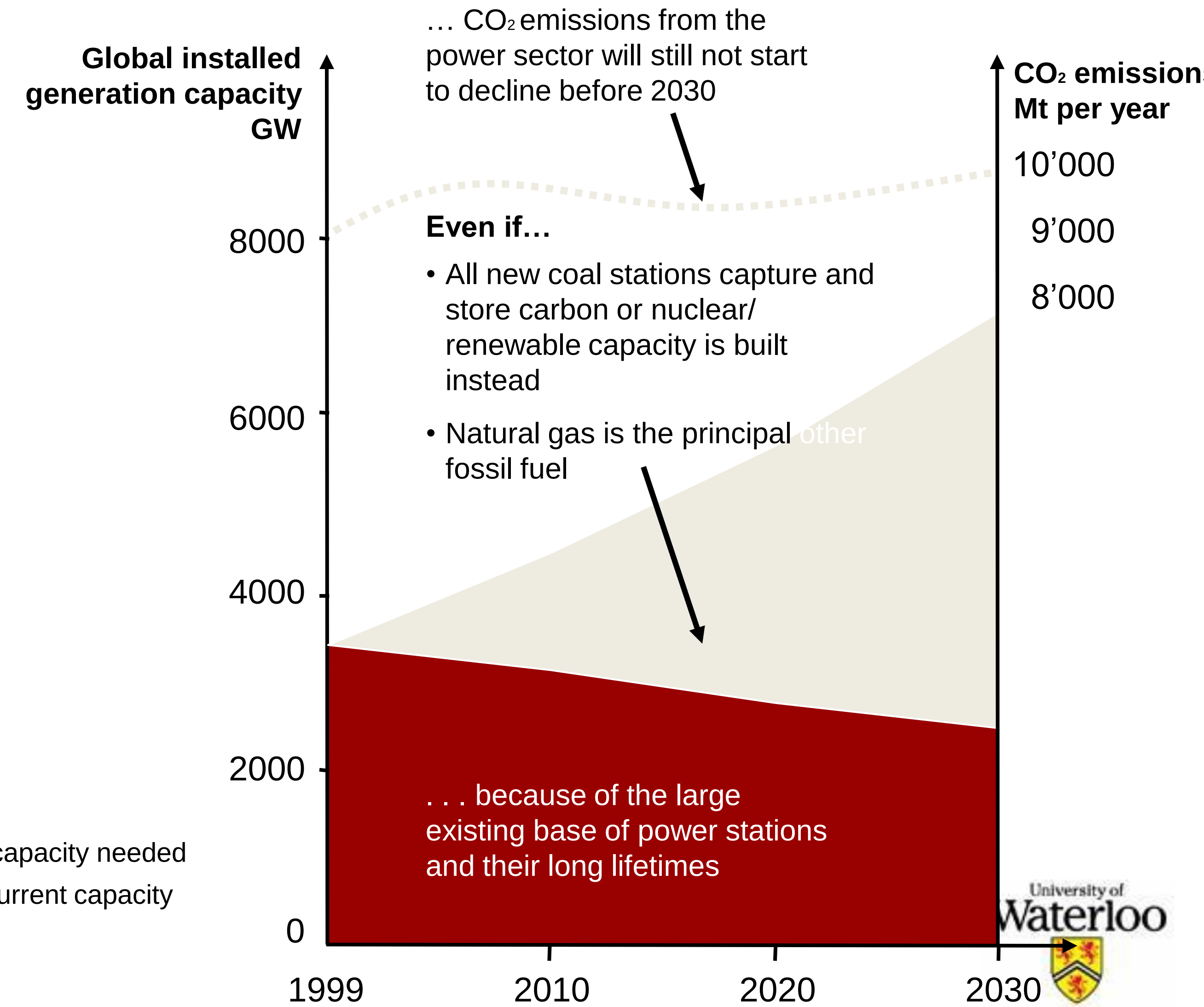
# Alternate power generation technologies: Impact on emissions



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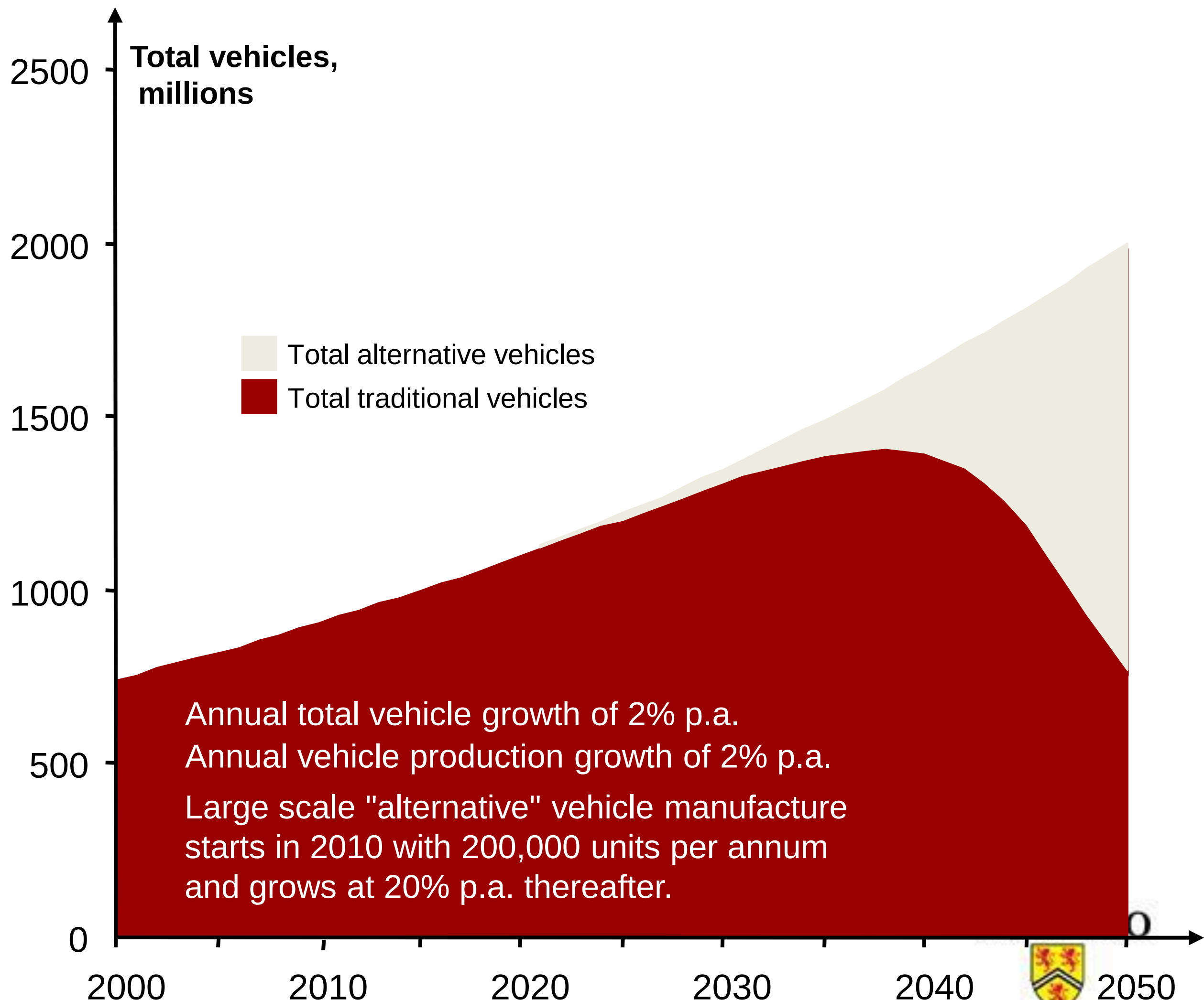
# Transport and Mobility



# Global Energy Mix:
# primary energy consumption and electricity

*Source:* IEA, 2006

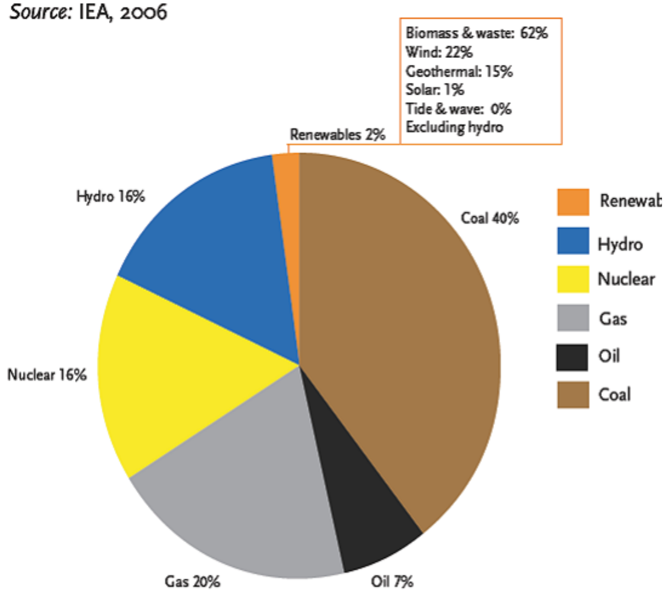



Figure 1.4 World electricity production by energy source, 2004

*Note:* Total world electricity production in 2004 was 17,408 terawatt-hou

*Source:* IEA, 2006.

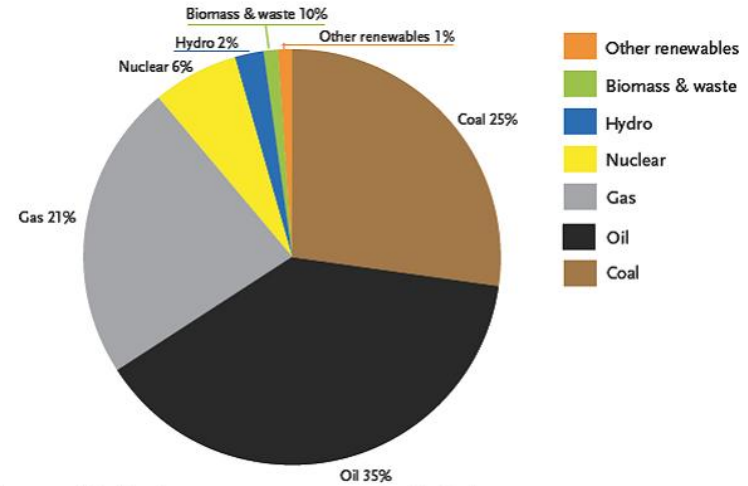



Figure 1.3 World primary energy consumption by fuel, 2004

*Note*: Total world primary energy consumption in 2004 was 11,204 megatons oil equivalent (or 448 exajoules).

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# Near Term View: Today and 2030

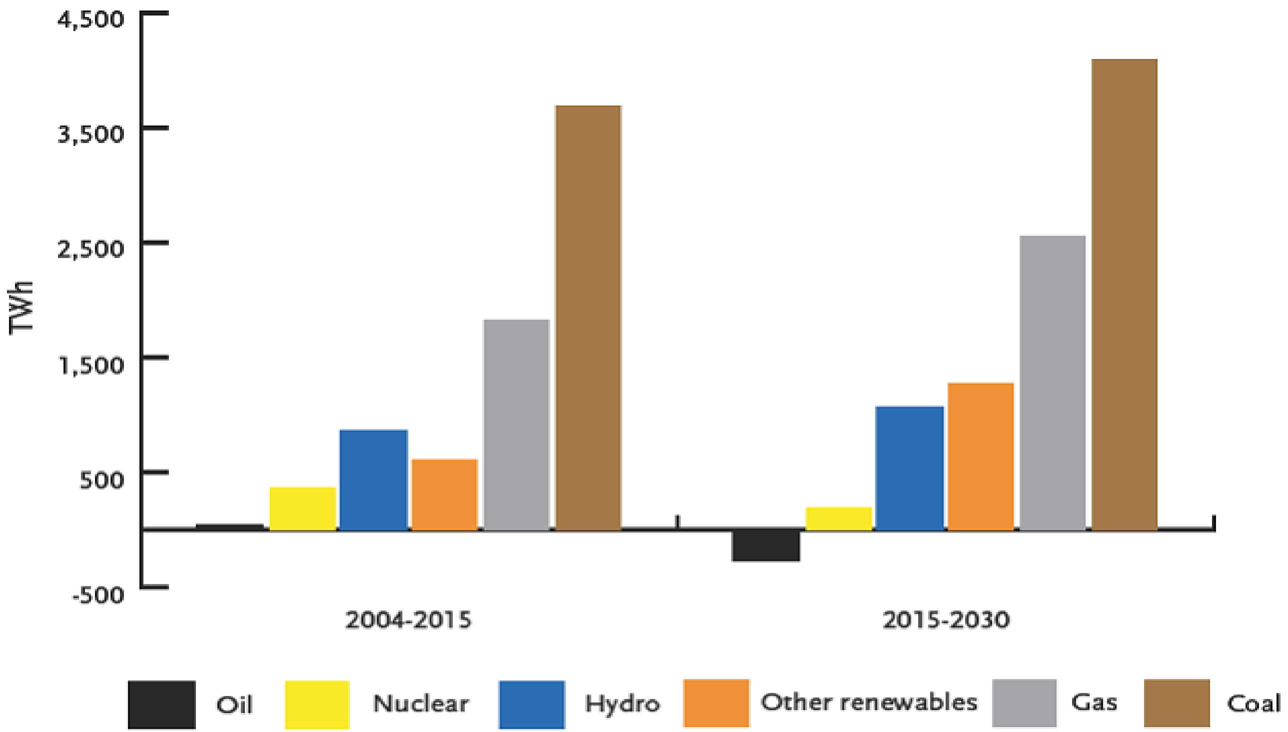


Figure 3.5 Projected world incremental electricity generation by fuel type

*Note*: 1 terawatt-hour (TWh) equals 3.6 petajoules.

*Source*: IEA, 2006

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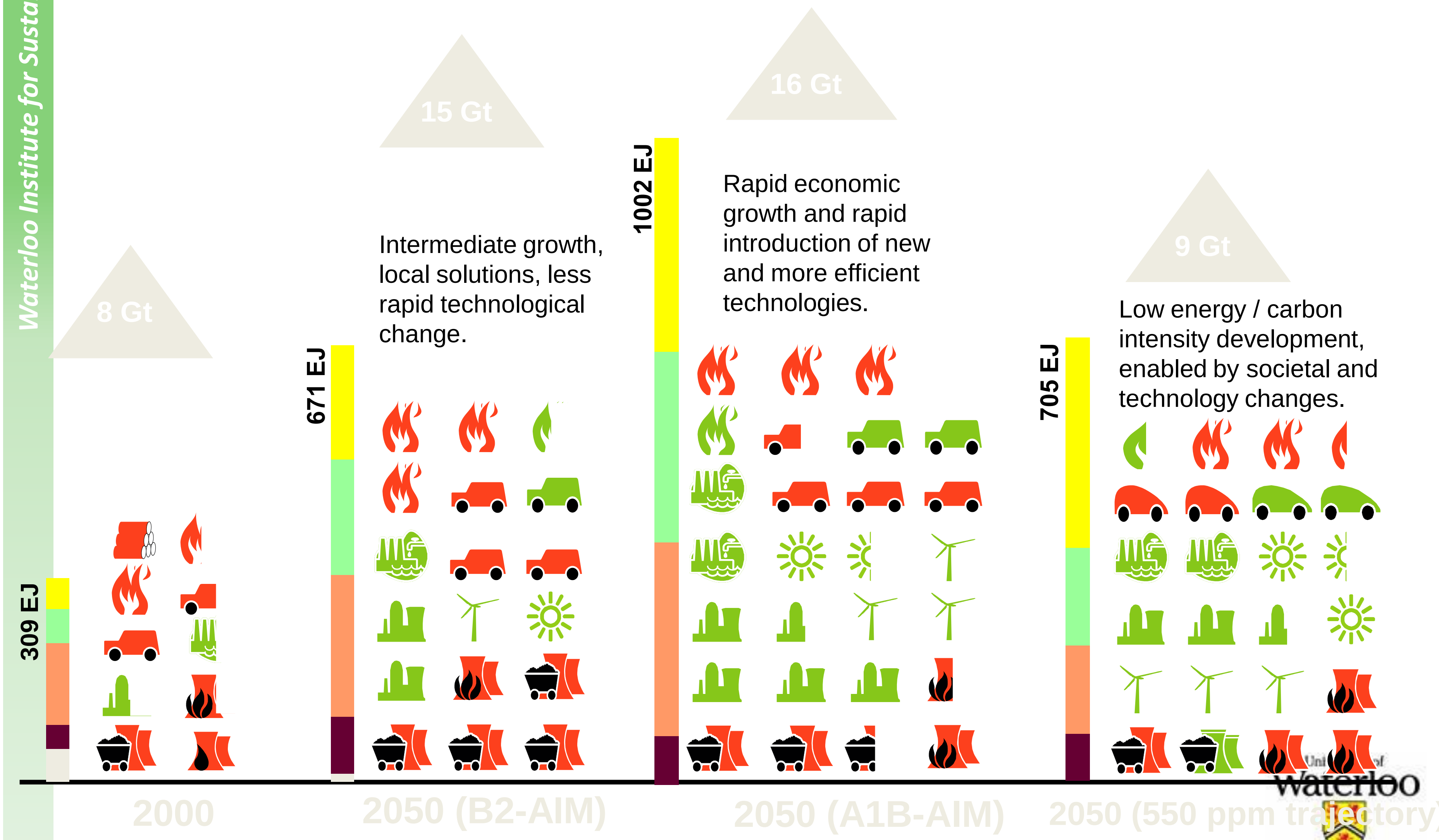
# A Balanced Mix of Options




Source: WBCSD, 2007

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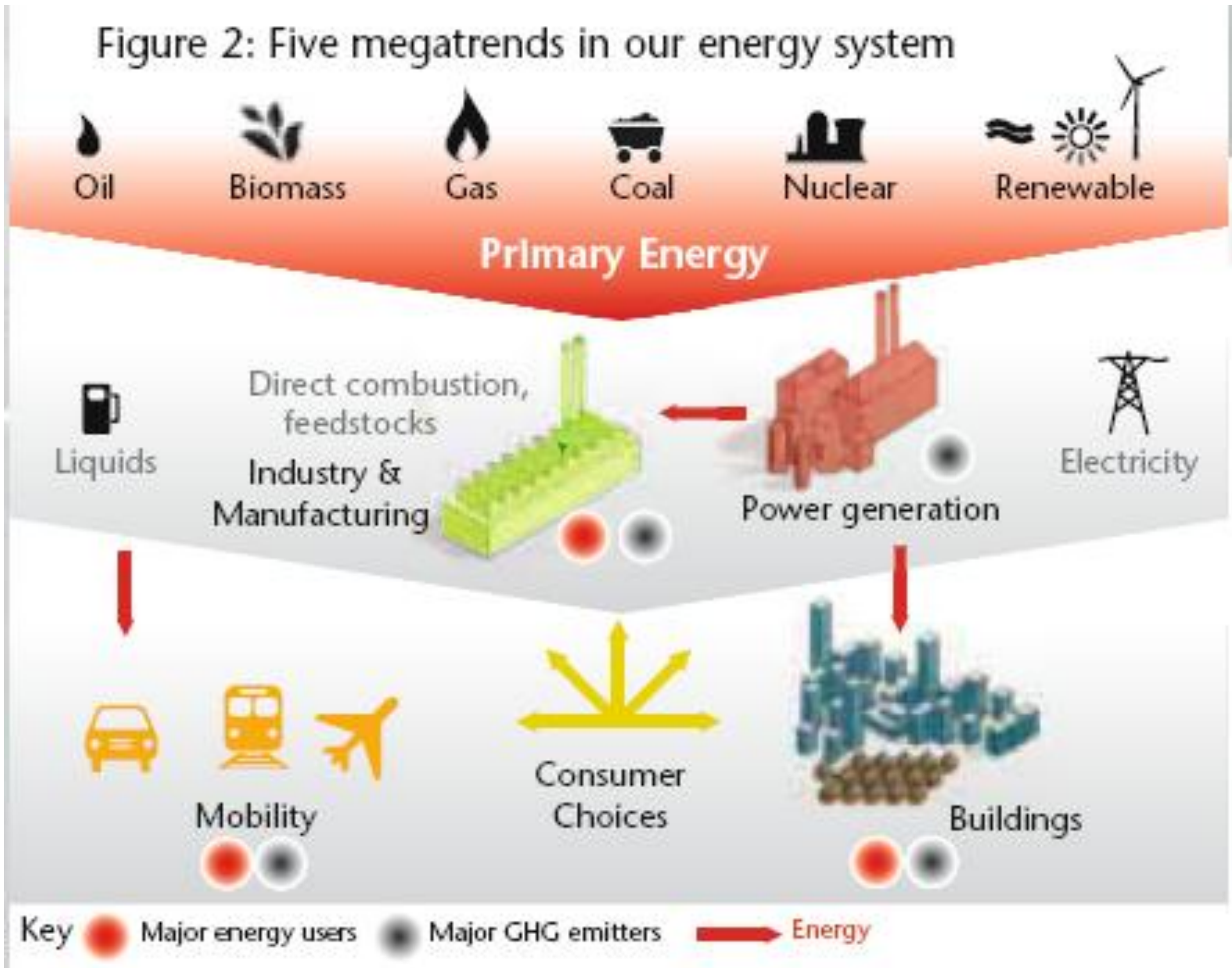
# Large changes in the energy system would be necessary over a 50 year horizon




Source: WBCSD Policy Directions to 2025, Nov 2007

# Energy Use : An Historical Perspective

- **The 20th century** offers a remarkable number of examples that are indeed a break from millenia past: all of them connected to dramatically higher use of energy.
  - **Revolution in food production** (dependent on fertilizers, pesticides and mechanization of agriculture)
  - **Mobility** (personal use of cars, air transport)
  - **Advances in communication** (radio, TV, satellites, internet..)
- All this has been possible through **abundant, inexpensive and precisely controlled energy.**
- **Perspective on our lives:**
  - We go to the nearest local market in our cars that generate the pull of hundreds of horses
  - We fly around the world with a power of a hundred thousand horses
  - Power consumption of the world today is the equivalent of 18 billion horses working 24 hours per day, every day of the year
  - Around 1900, Great Plains farmer in Nebraska: 5kW steady power; a century later, his great grand child, sitting in an air-conditioned stereo enlivened comfort of a tractor's cabin would deliver 300kW of power with the mere physical exertion of the task of typing.
  - In 1900, an engineer operating a powerful transcontinental train (100 km/h speed) commanded about 1MW of steam power. A century later, the pilot of a Boeing 747-400 controls 45MW, and retraces the same route 11km above the earth's surface at an average speed of 900km/hour)
  - In 1900, a chief engineer at one of Europe's or North America's utility companies controlled the flow of no more than a 100kW of power. A century later, the duty dispatcher at Ontario's grid control centre can re-route a 1,000 MW of power (four order of magnitude larger).

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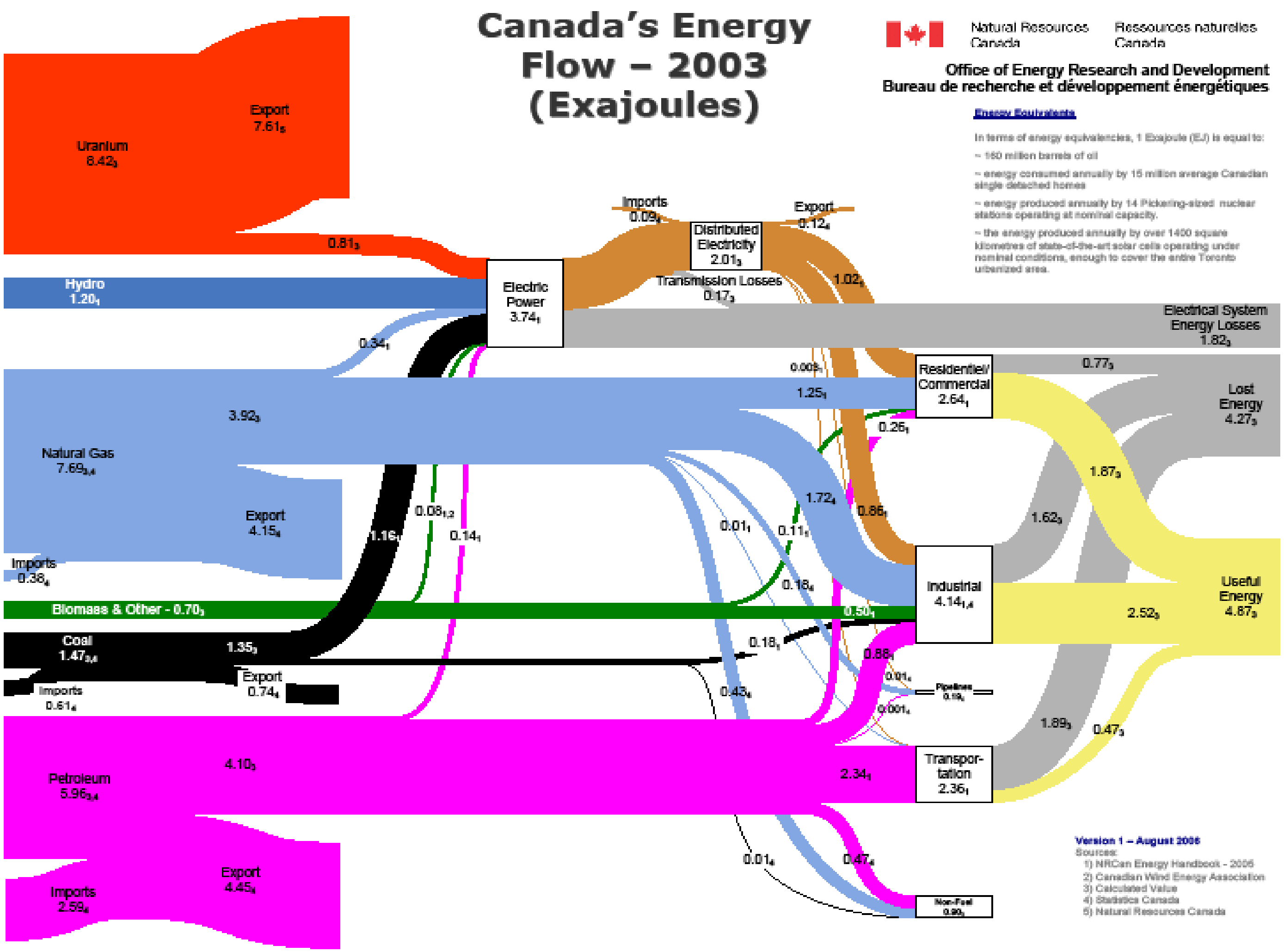
# Electricity as a vector of change:

## A look at the contrast between energy and electricity

# It takes a lot of energy to get to useful energy



# Electricity and Energy Contrast

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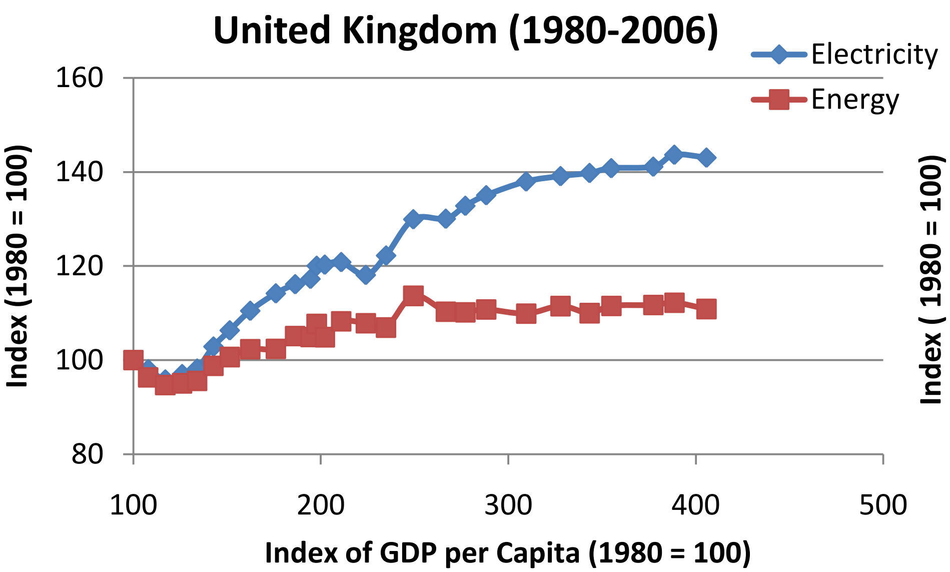


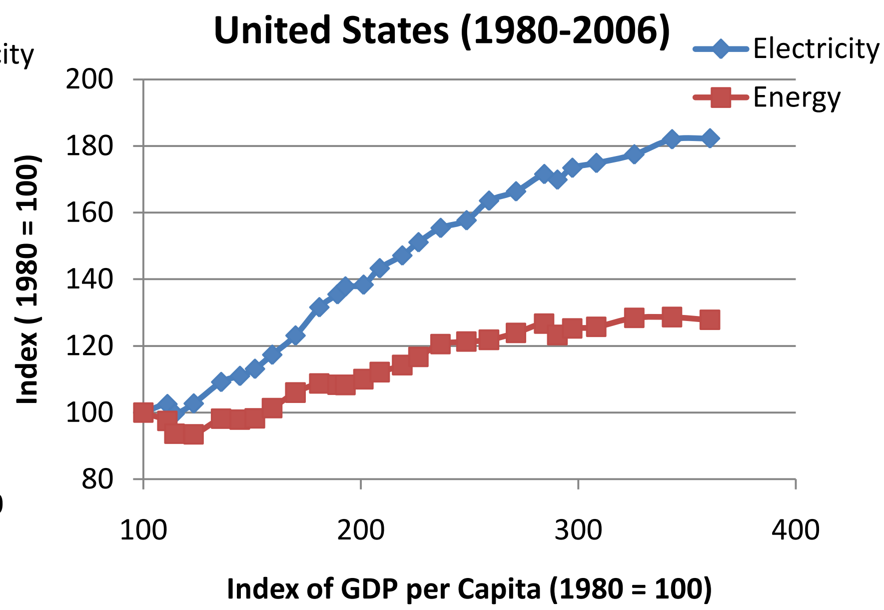


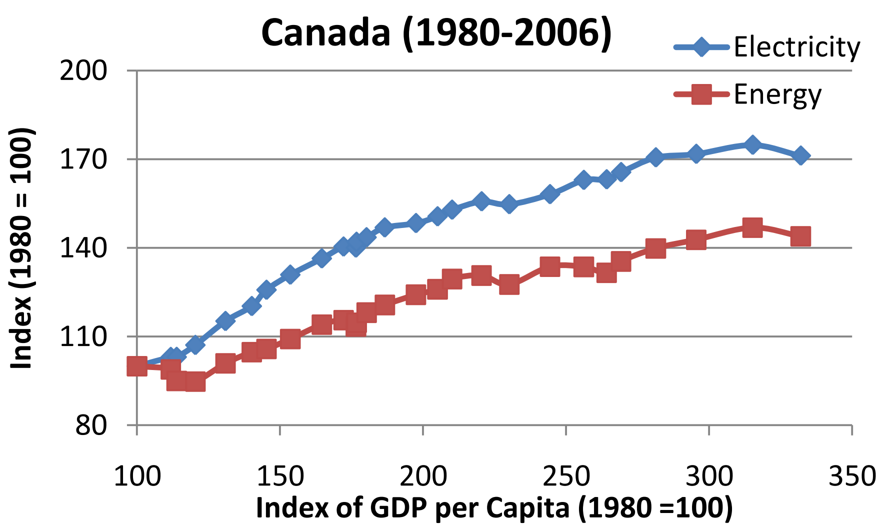


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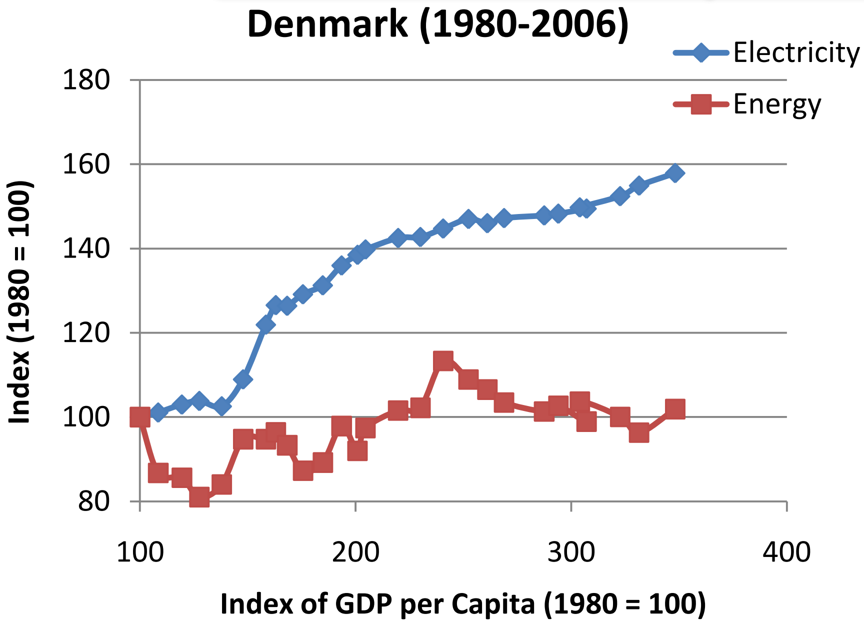


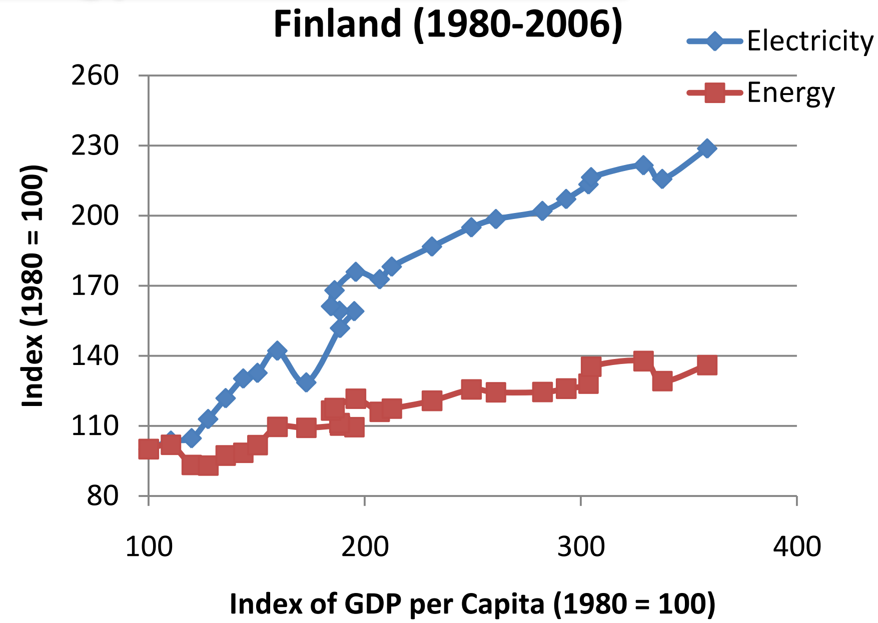


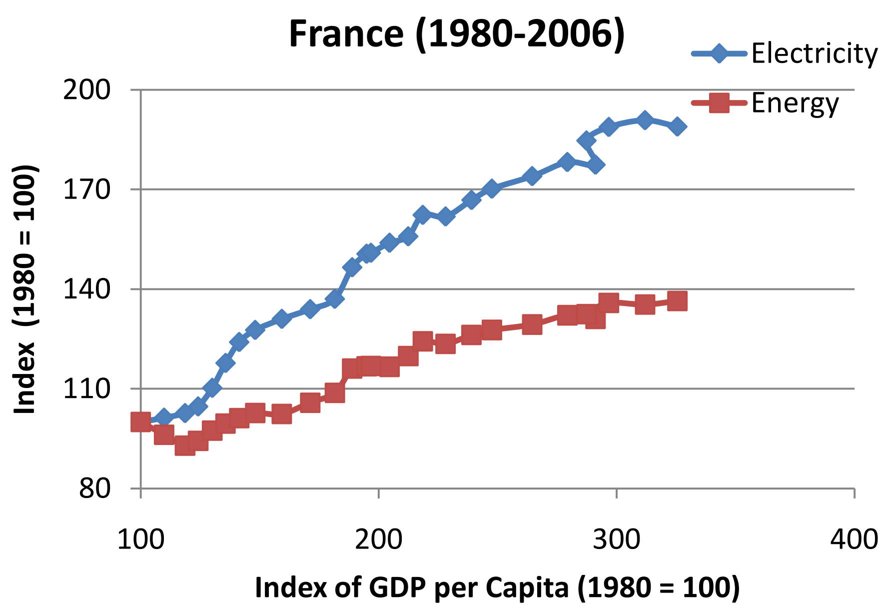


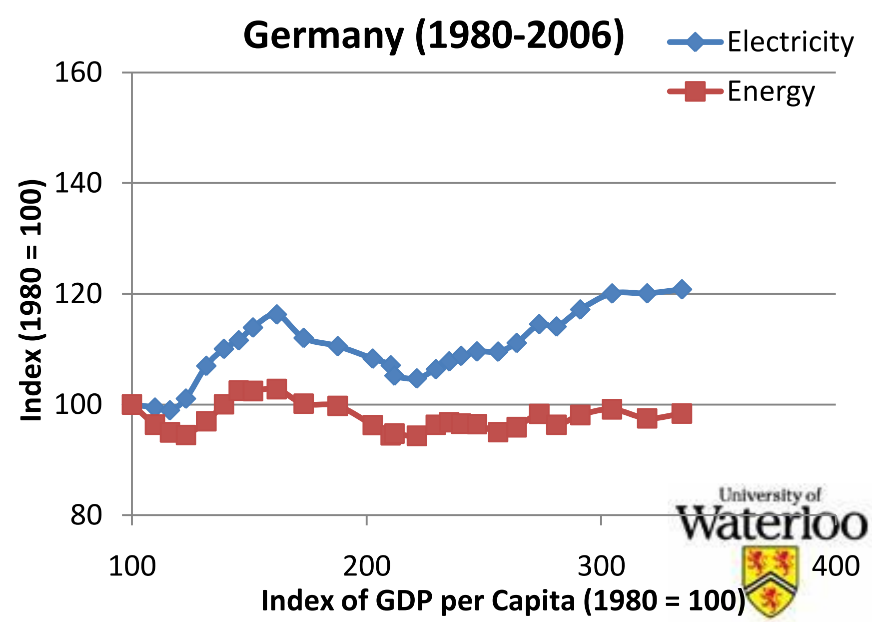


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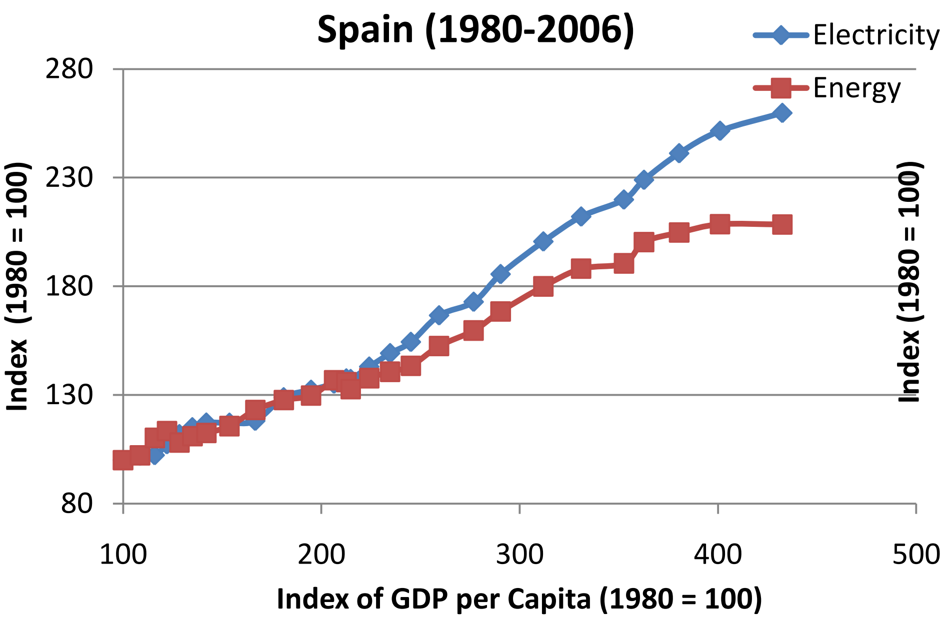


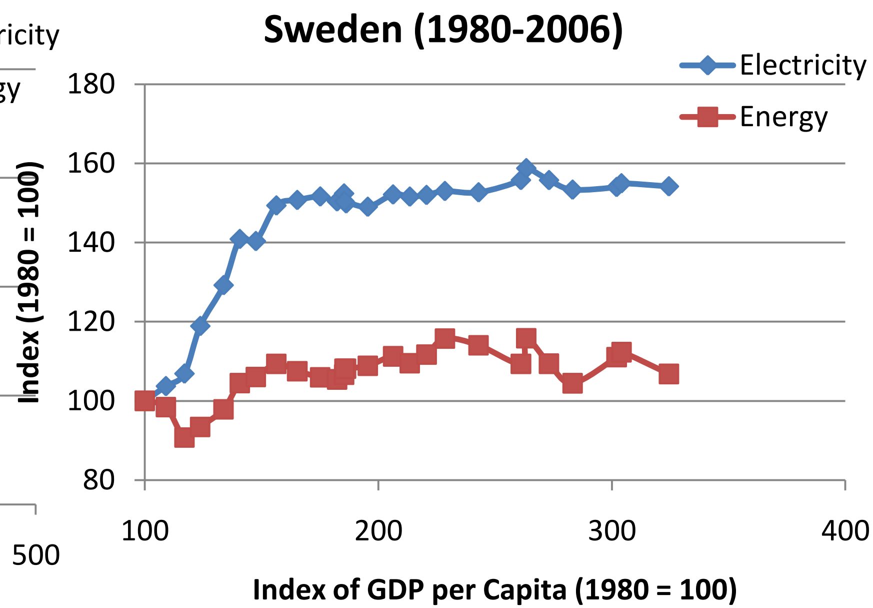


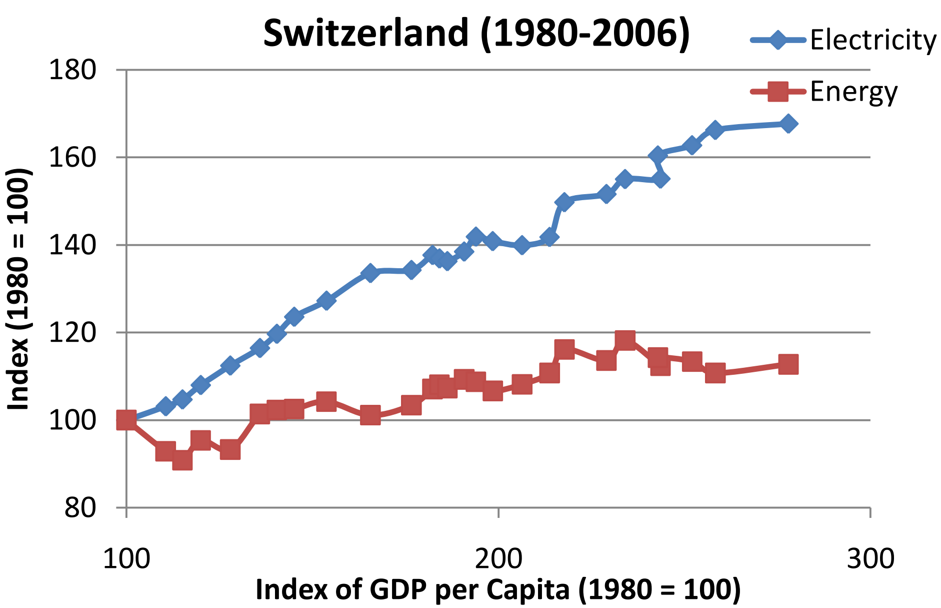


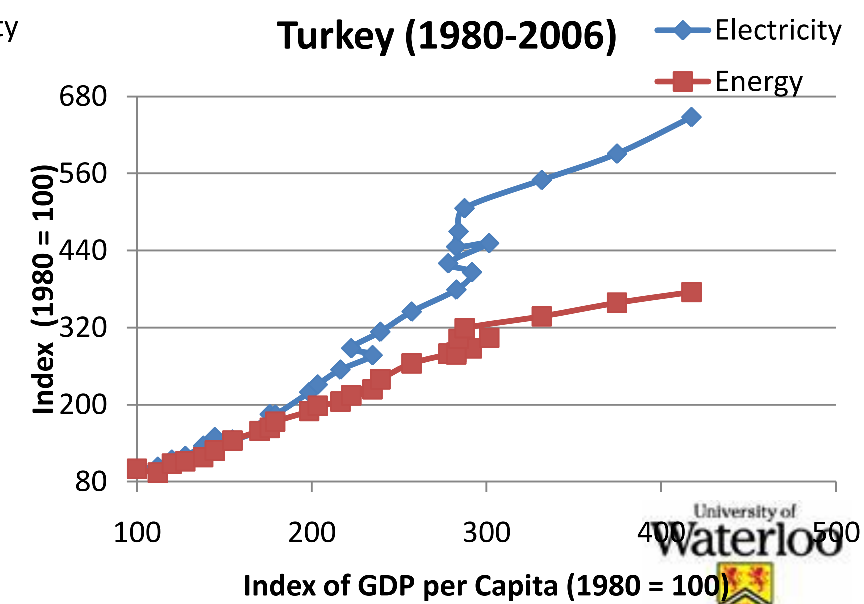


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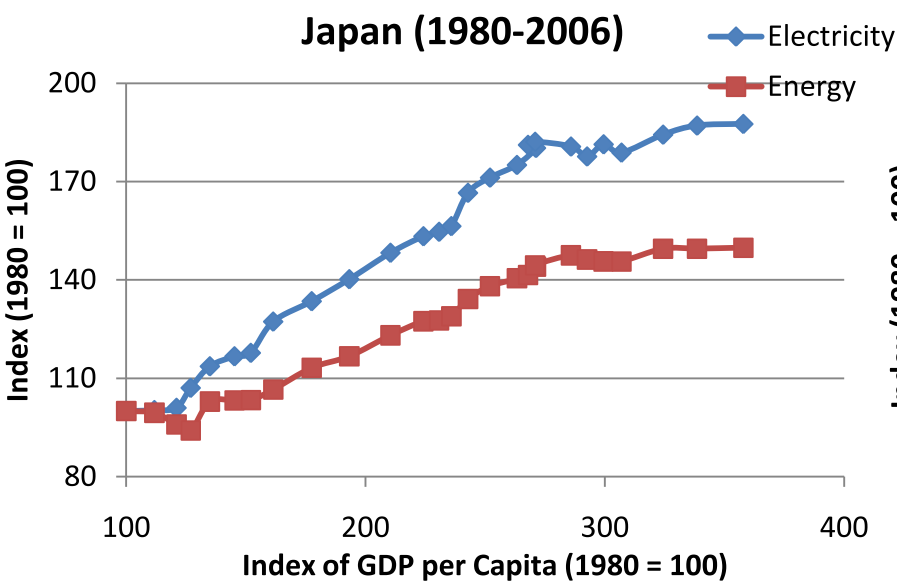


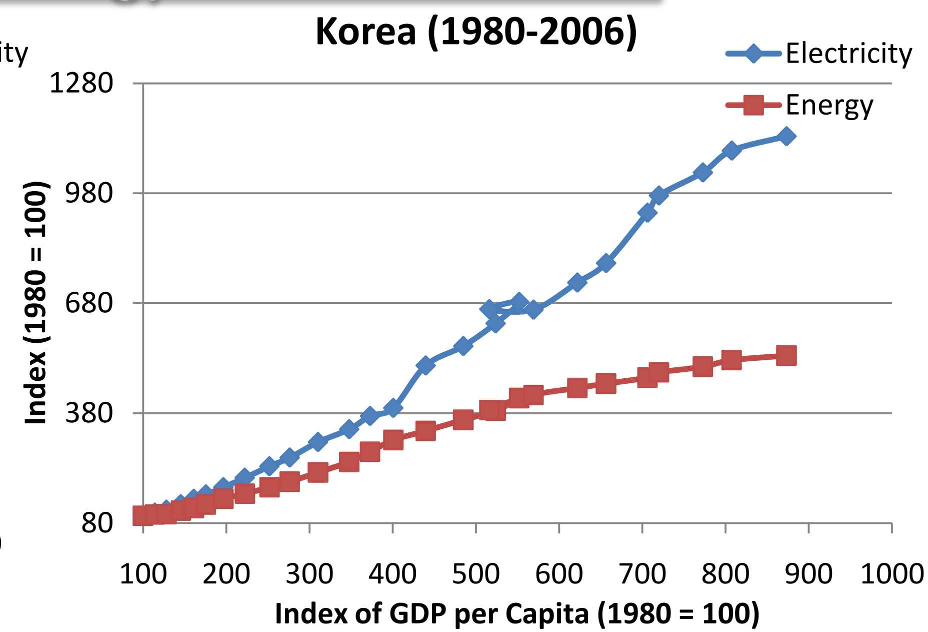


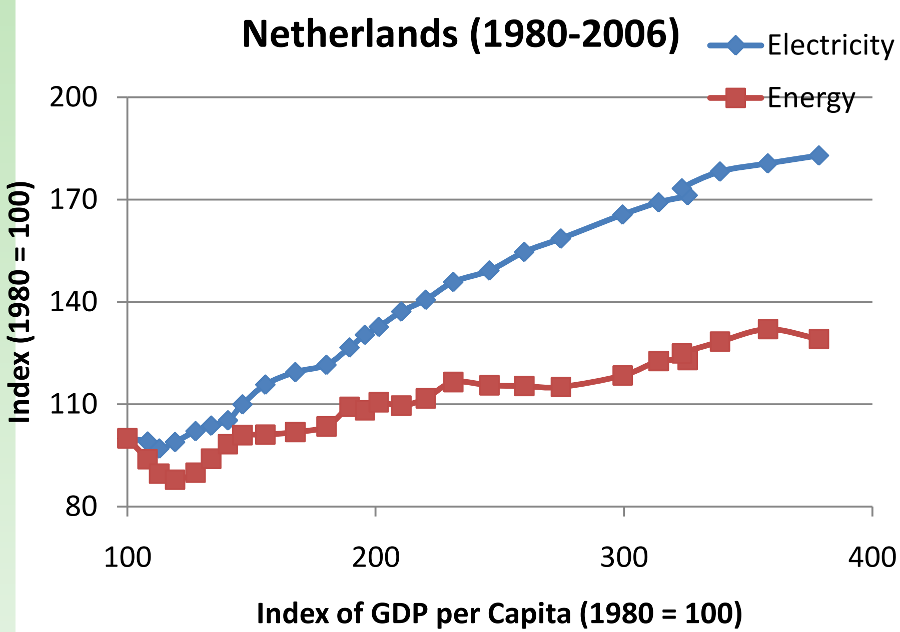


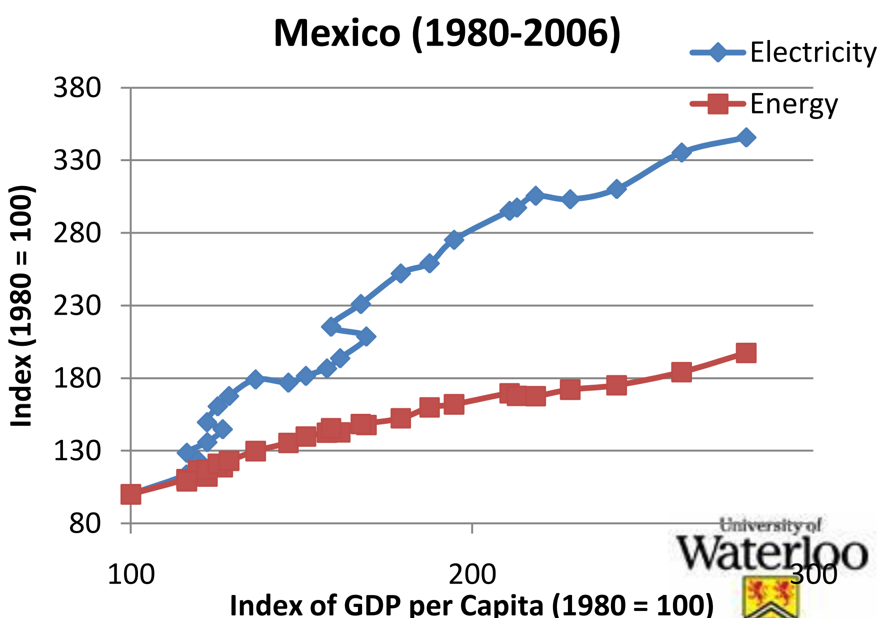

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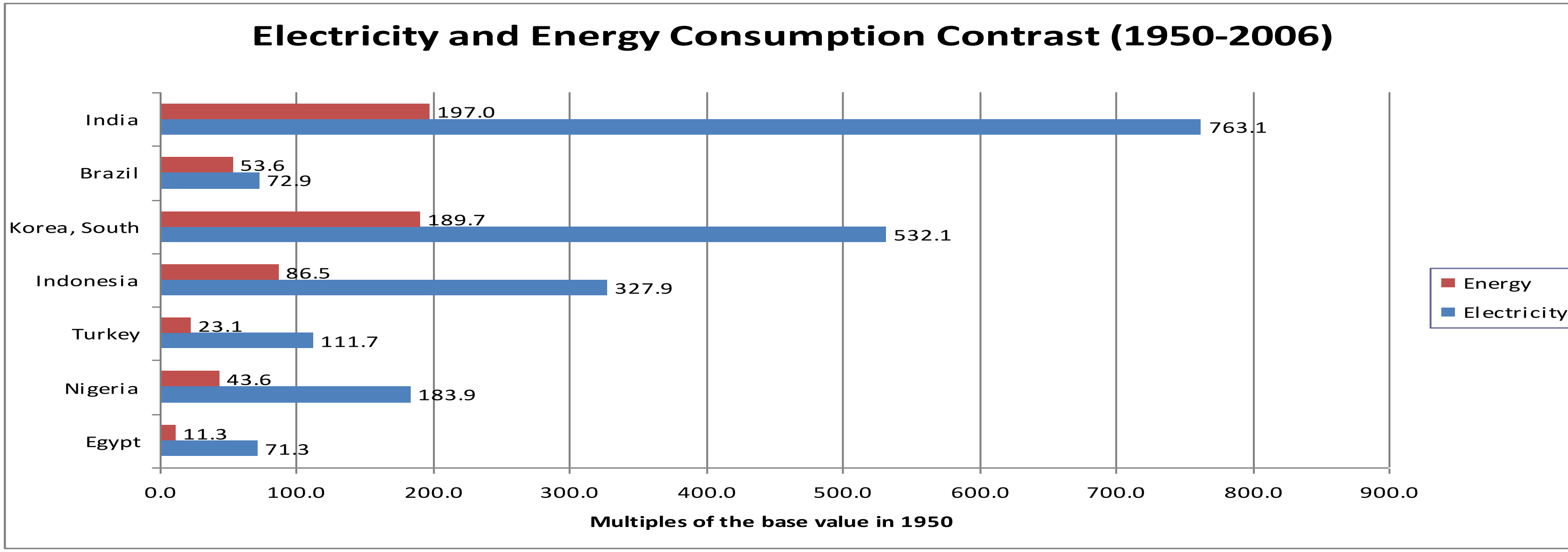
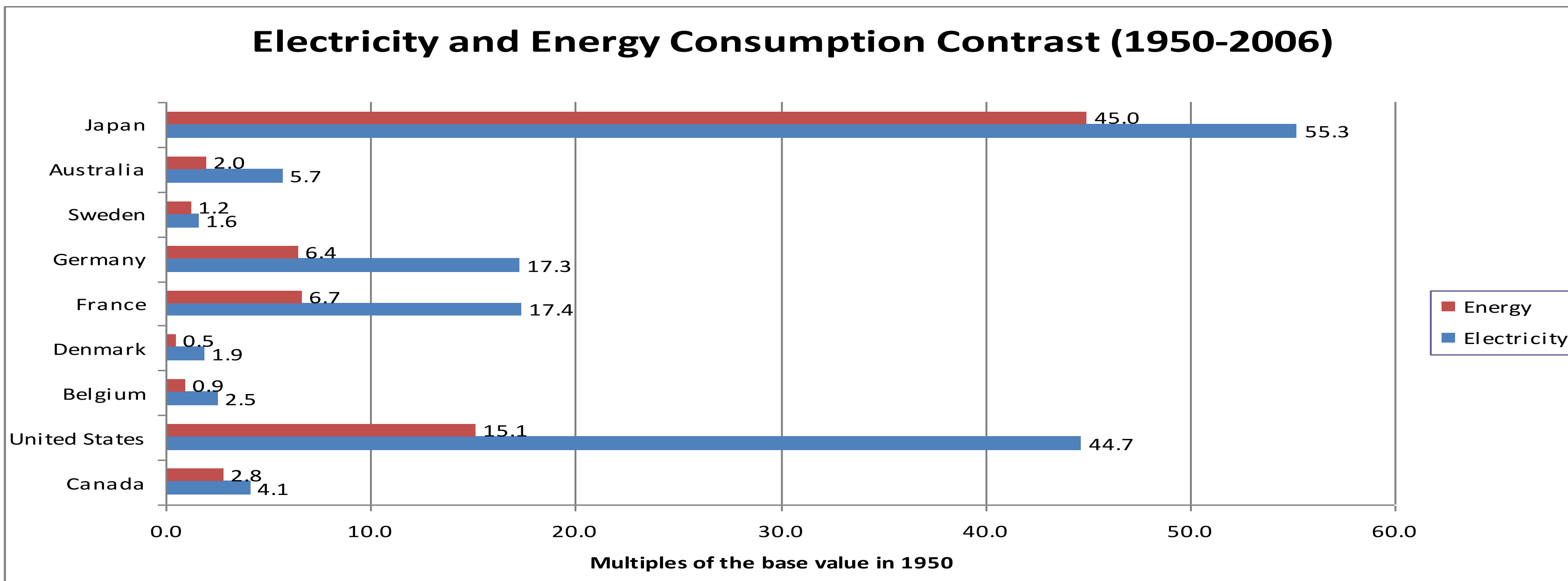


# Global trends

1. Five major trends in the energy system relate to
   - power production, transport (mobility), manufacturing and industry, buildings and consumer choices
2. Doubling (2x) or tripling (3x) of global energy demand
3. Climate change challenge and a carbon constrained world
4. Efficiency in energy conversion from primary fuel to end use
5. Global trend is towards electrification of the economy
   - High Value, Ubiquitous
   - Over 100 years, US primary energy consumption rose **10x**; electricity consumption rose **30x**
6. Electrification: A Blessing In Disguise?
   - Close coupling of electricity with wealth creation as opportunity
   - Increasing electricity share as opportunity for decarbonising the economy

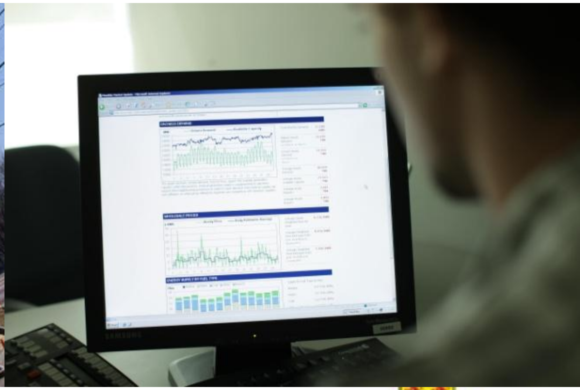
# Why Smart Grids?




# Ontario Smart Grid Forum

- Industry leaders brought together to develop a smart grid vision for the province
- Vision designed to guide:
  - a co-ordinated approach across the sector
  - the mitigation of technology risks
  - the development of capital investment plans
  - a supportive regulatory framework



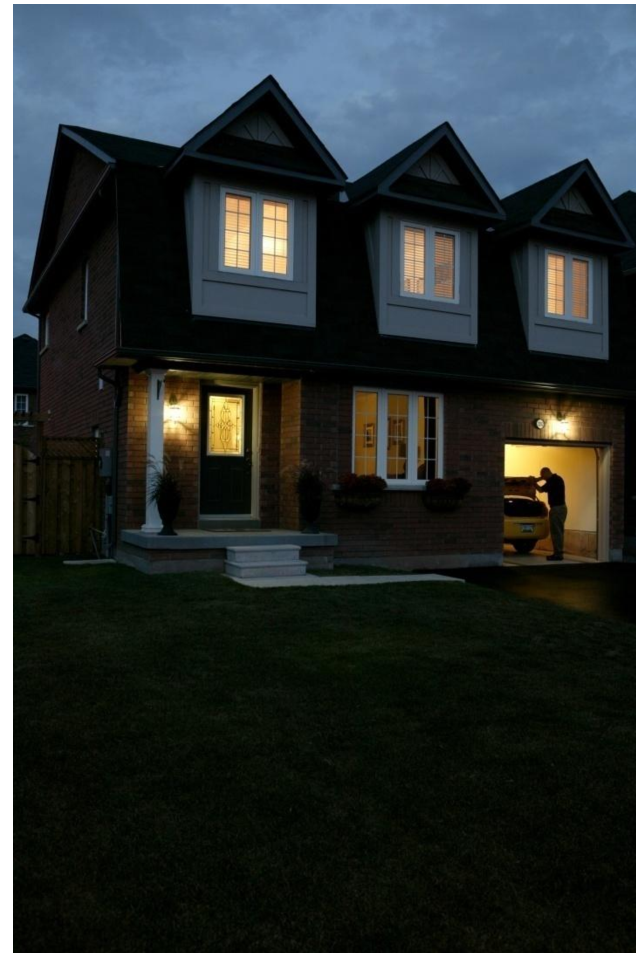


# What is a Smart Grid?

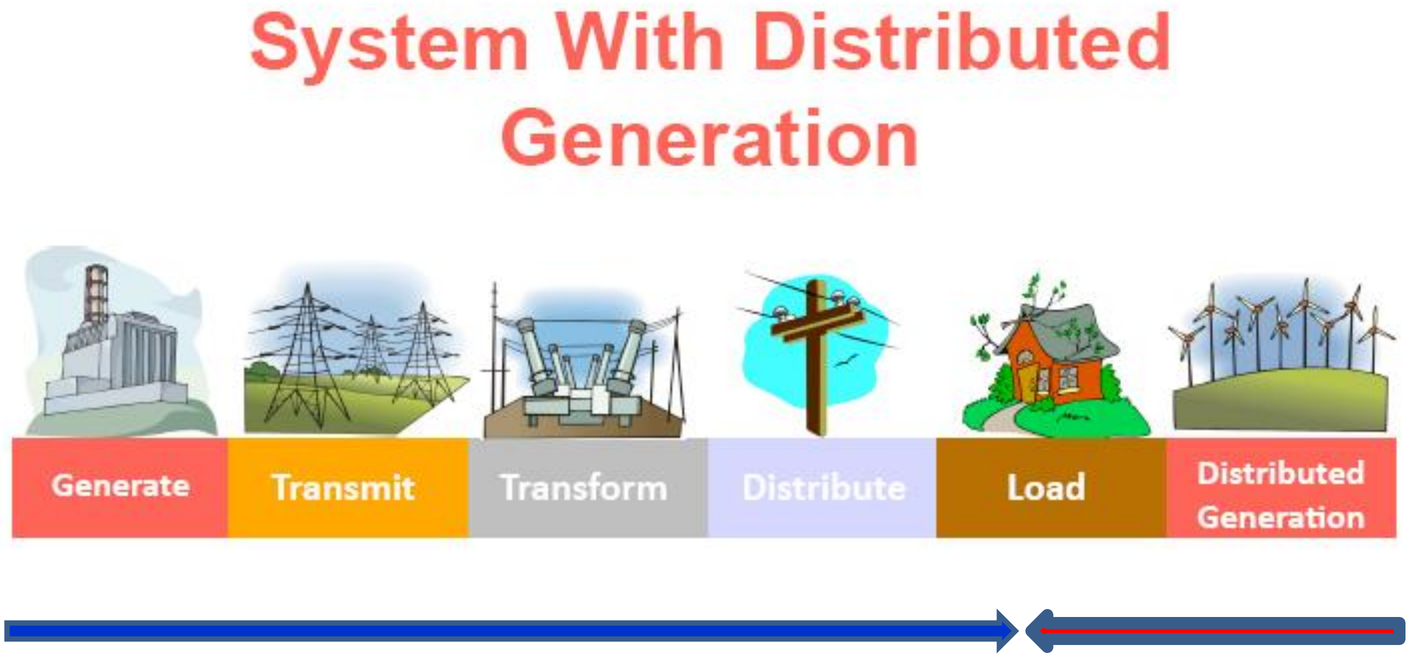
- Smart grids comprise sensors, monitors and information technology – bringing together all elements of the electricity system
- They include distributed generation, accommodate electric vehicles and provide greater consumer choice

# Smart Grid Benefits

- Modernizing the electricity system to serve the digital age:
  - Better integration of renewables and distribution generation
  - More efficient use of energy infrastructure and reduced energy losses
  - Empowered consumers with increased participation in conservation and demand response
  - More reliable distribution service with reduced outages and quicker response times



# Paradigm shift: power flows both ways



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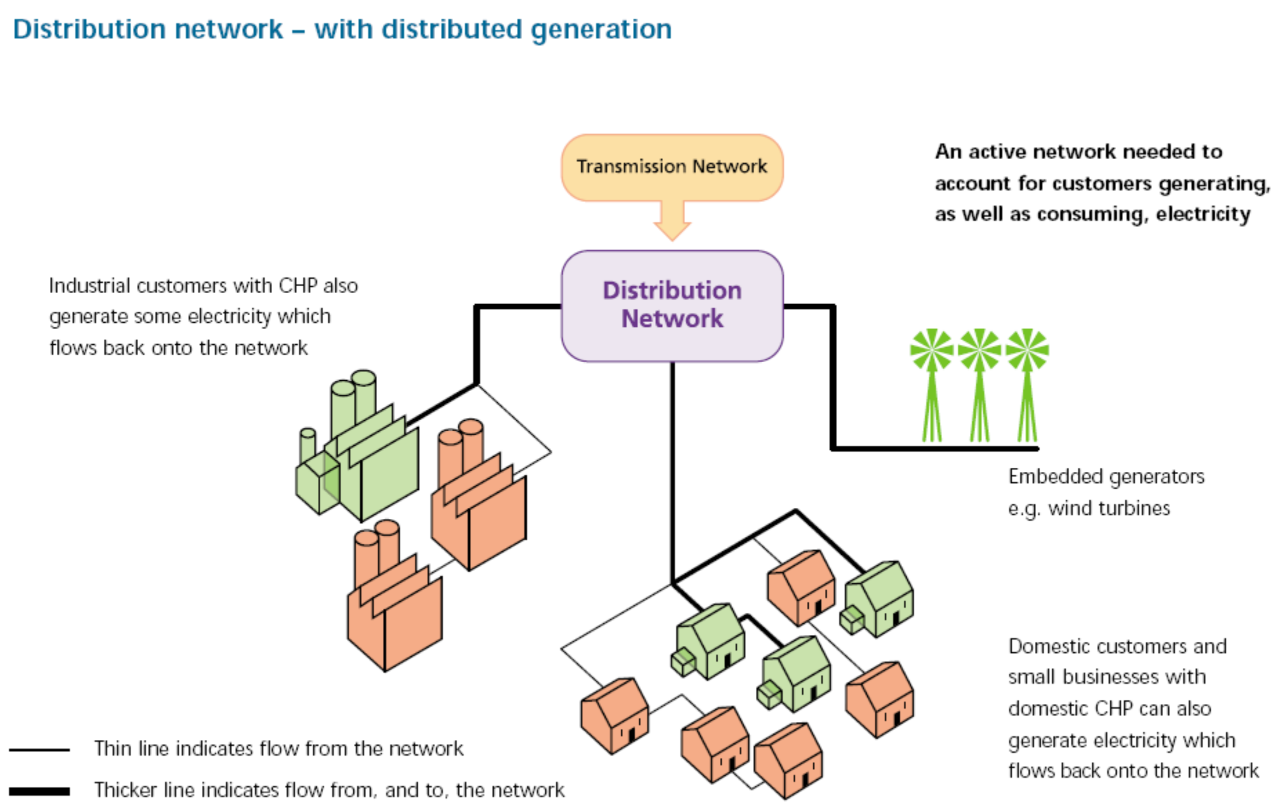


Source: Ofgem 2003



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# DG Technologies and Characteristics

- Wind power (small projects with outputs from 50kW to 10MW)
- Biogas and biomass (landfill sites, agricultural and livestock operations, wood forest residues, wastewater treatment facilities:1-10MW)
- Combined Heat and Power (CHP) schemes including micro-CHP (residential 1kW-25 kW) and Stirling engines (1kW to 55kW)
- Solar photo-voltaic (PV) cells (50kW- 1MW)
- Fuel cells (1kW to 1MW)
- Microturbines (20-100kW)
- Natural Gas reciprocating engines (30kW- 3MW) and dual fuel reciprocating engines (90kW- 2MW)
- Gas and diesel fired combustion turbines (>1MW)
- Large DG applications & mobile systems for standby generation
    - (0.5 to 2MW),
    - peaking (1-5MW)
    - T&D support (0.5-10MW modules) and crisis operations

# Distributed Generation Resources: Cautions

- Performance has not equaled promise
- Fuel cells, micro turbines, solar photovoltaics
  - Still too expensive
- Fundamental business case?
  - Availability of "cheap" fossil based energy either as back-up or primary use
- Transmission and Distribution
  - Capital deferral, utilization, congestion (some potential but not demonstrated)
  - Integration with distribution system required and can be costly

# Getting There: Innovation

- **New technologies need to be invented and brought to market**
  – opportunity to create green jobs
- **Sustained and significant investments are required**
- **What role can innovation play to**
  - Reduce cost
  - Improve reliability of service
  - Improve environmental performance
  - Enhance economic performance



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# The Power System That Evolved in Late 19th Century to Provide Power to the Newly Invented Light Bulbs .........

1879 - Thomas Edison Developed a "Practical Light Bulb"


Line crew of Niagara Falls Power Co. in 1895



GALVIN

# …….. has Remained Essentially the Same as it Powers the Essential Services and the Digital Revolution in the 21st Century

**August 29. 2005**: Power poles are pushed over in a flooded street after Hurricane Katrina

- → Powers the critical pumps that takes water out from New Orleans and makes drinking water in a water treatment plant
- → Powers the communication towers and central telephone stations that are essential for the communication infrastructure
- → Powers the essential life saving services in a hospital
- → Powers the continuous process industries that are the life blood of an industrial society
- → Powers the computers, servers and routers that enable the digital revolution

# The "not so smart grid"

# The GEA Sets the Framework for a Smart Grid…

The GEA sets the objectives and framework for smart grid to "improve the flexibility, security, reliability, efficiency and safety" of the electricity grid.

| ***GEA Smart Grid Objective*** | ***Focus Area*** | ***Expected Outcomes*** | |
|---|---|---|---|
| i. "expanding opportunities to provide demand response, price information and load control to electricity customers;" | **Customer Control** | • Smart meters<br>• Time-of-use rates<br>• In Home Displays<br>• Load control | More Conservation |
| ii. "enabling the increased use of renewable energy sources and technology, including generation facilities connected to the distribution system;" | **Utility Flexibility** | • Customer based micro-generation<br>• More distributed generation, used more efficiently<br>(i.e. less transmission investment) | More Renewables |
| iii. "accommodating the use of emerging, innovative and energy-saving technologies and system control applications;" | **Adaptive Infrastructure** | • Mobile charging infrastructure to support EVs<br>• Storage opportunities<br>• Keeping room for innovative technologies | More Innovation |

# Need to change the lens through which we see the power sector

1. More positive frame
2. Electricity as driver of change
3. Boost economic development
4. Act as the “cleaning agent” for the transport sector by using electrons to displace gasoline
5. Promote the long view

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# SUSTAINABLE ENERGY:
## Policies, Programs, Directions

- Social marketing
- Sustainable building
- Demand management
- Conservation behaviour

- Hydrogen production
- Fuel cells (solid oxide and PEM)
- Thermoelectric materials and devices
- Lithium ion batteries


- Centre for Advanced Photovoltaics Systems & Devices (**CAPDS**)
- Solar thermal applications
- Wind turbine design and performance
- Bioenergy
- Distributed generation

- $CO_2$ capture, storage & mitigation
- Clean diesel engines
- Clean coal technology
- Nuclear power plant reliability

- Sustainable energy policy and planning
- Sustainable urban design
- Emissions reduction
- Green batteries
- Green auto power train

- Power quality
- Energy systems reliability
- Large scale optimization
- Energy forecasting
- Electricity markets

**Preserve & Create Energy Options**
**Multi-Disciplinary Research Teams**
**Economic Growth & Environmental Performance**
**Business, Government, Industry , Civil Society Engagement**

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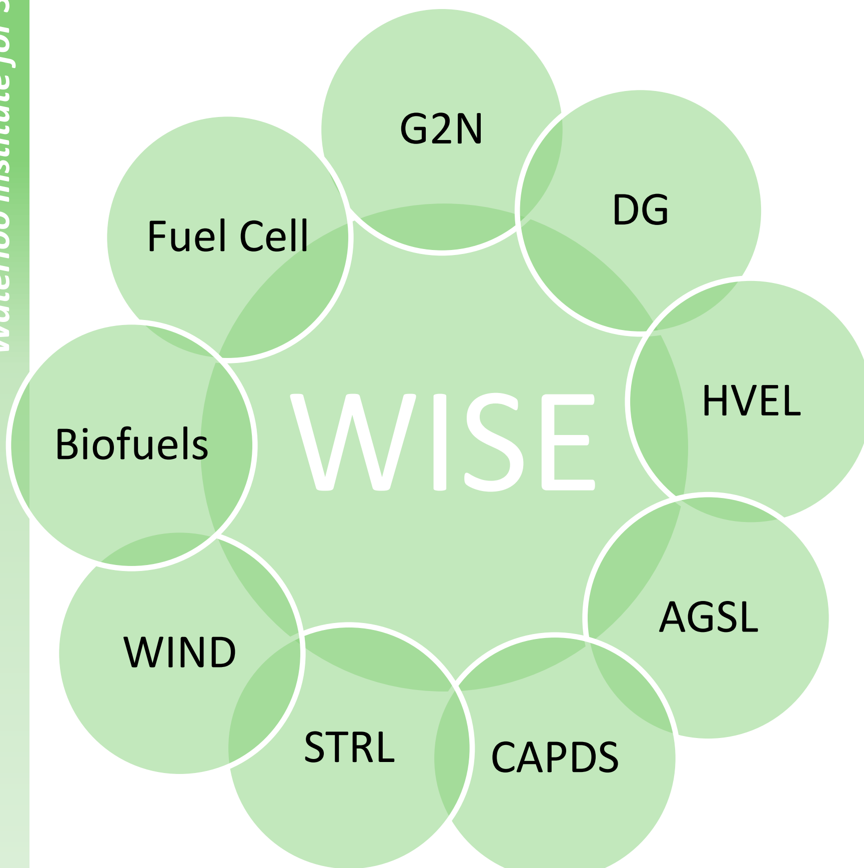
# The Waterloo Institute for Sustainable Energy (WISE)




### G2N Giga-to-Nano Lab
- Andrei Sazonov, Electrical & Computer Engineering

### DG Distribution Generation Lab
- Ehab El-Sadaany, Electrical & Computer Engineering

### HVEL High Voltage Engineering Lab
- Shesha Jayaram, Electrical & Computer Engineering

### AGSL Advanced Glazing System Lab
- John Wright, Mechanical & Mechatronics

### CAPDS Centre for Advanced Photovoltaic Devices and Systems
- Siva Sivoththaman, Electrical & Computer Engineering

### STRL Solar Thermal Research Lab
- Michael Collins, Mechanical & Mechatronics

### WIND Lab
- David Johnson, Mechanical & Mechatronics

### Biofuel/Biomass Lab
- Ray Legge, Biometric Engineering & Environmental Engineering

### Fuel Cell Lab
- Michael Fowler, Chemical Engineering

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# Select Highlights

## 3 Signature Projects

***Decreasing Diesel Dependency in Remote Northern Communities***

- Off-grid hybrid power system provides a lower-cost, environmentally friendly solution for remote communities.

***Energy Consumption Management System Gives Consumers Control***

- A smart web-based tool gives consumers control to change the way they use energy, and move to on-site alternatives like solar and wind energy.

***Connecting Solar Farms to the Grid***

- UW and U Western are developing comprehensive solutions to help grid operators incorporate large-scale solar farms to their networks.

- Smart Grid Forum
- Plug-In Hybrid Electric Vehicles Ontario Action Plan
- "Affordable solar for the masses"- A major international initiative
- Integration of Distributed Generation into system
- Advanced batteries and storage technologies

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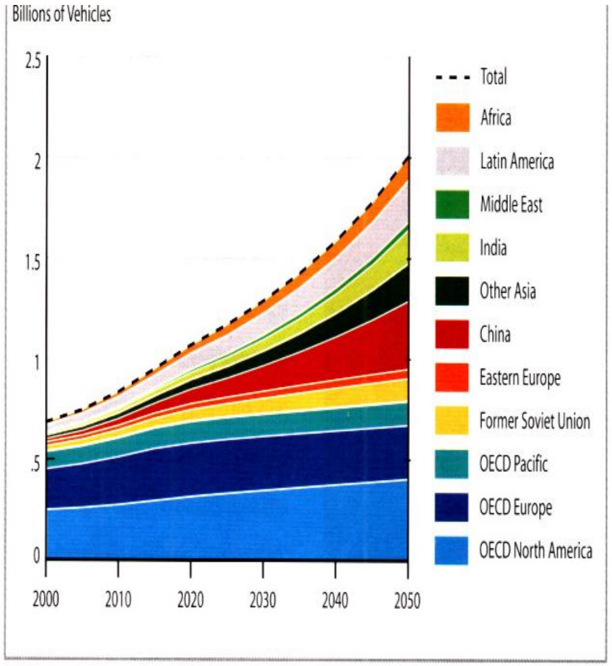
# Sustainable Mobility




Source: Sustainable Mobility Project calculations.

## Don't step back in technology When we move forward to Energy Sustainability

These technologies are **not** sustainable with today's population!!

- Powered by lithium-ion battery
- Charges in under 1 minute.
- Range: 15 km at 40 km/h.
- Cold weather testing in Sapporo next month.
- Uses 10% less energy than existing streetcars.

**New UCDavis PHEV that will run on Sunshine *40mi/day* and a little Ethanol**

**Can be ZERO** gasoline or diesel Now for the avg. driver!!!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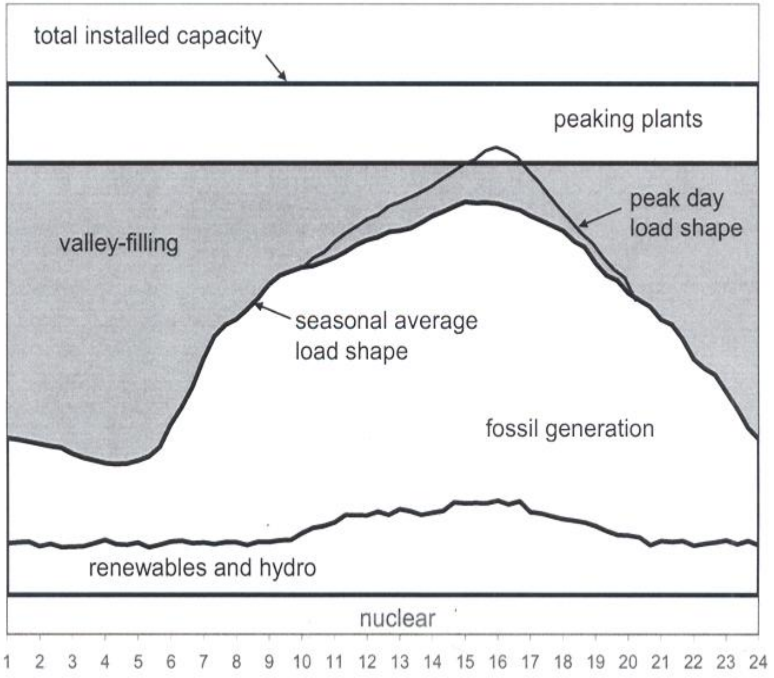
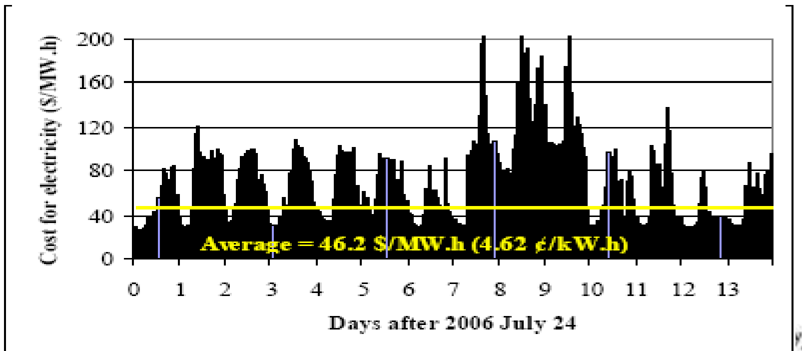
# Low cost electricity to displace gasoline
# "green electrons as substitutes for carbon"




- Assume vehicles will recharge between midnight and 6 a.m.
- Select lowest-cost periods
  - Either 1 hour, 2 consecutive hours, or 3 consecutive hours
- Convert to annual demand
  - Typical Canadian light vehicle covers 20 000 km/a
    - 45% highway at 21.1 kW.h/100 km; 55% city at 16.8 kW.h/100 km
    - 3370 kW.h/a
- This will be new generation at off-peak periods with no obvious market
  - Could be used to recharge 2.72 million vehicles (one-third of the Ontario fleet) between midnight and 6 a.m.
- Estimated annual fuel cost
  - Around 100 $/a
  - Compared to gasoline at 720 $/a (before taxes)



2 kW EV Charging Station


10 kW EV Charging Station

30 kW EV Charging Shade Structure

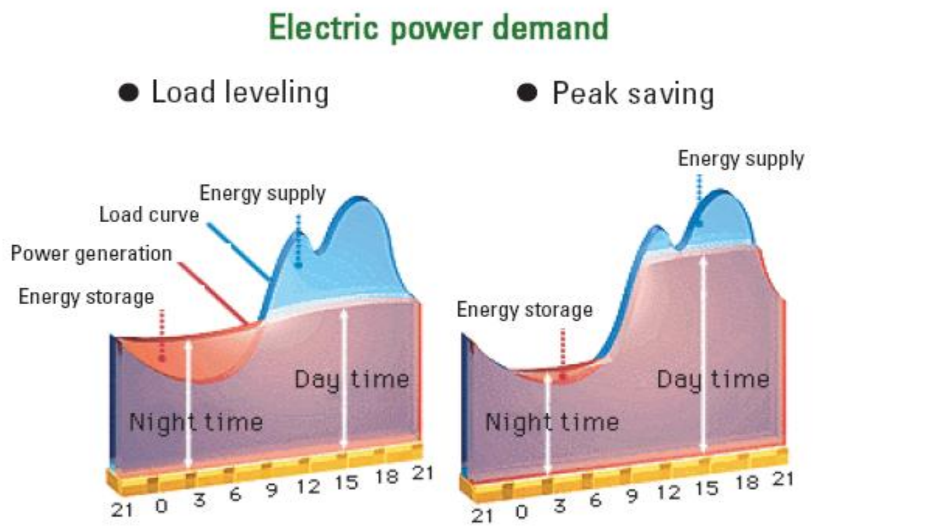
300 kW EV Charging

Source: steve@renewables.com

# Distributed Energy Resources- Energy Storage



- Electricity storage: Key requirement for a grid with large DG and renewables




*Source:* Tokyo Electric Power Company

- Convergence of grid and transportation infrastructures?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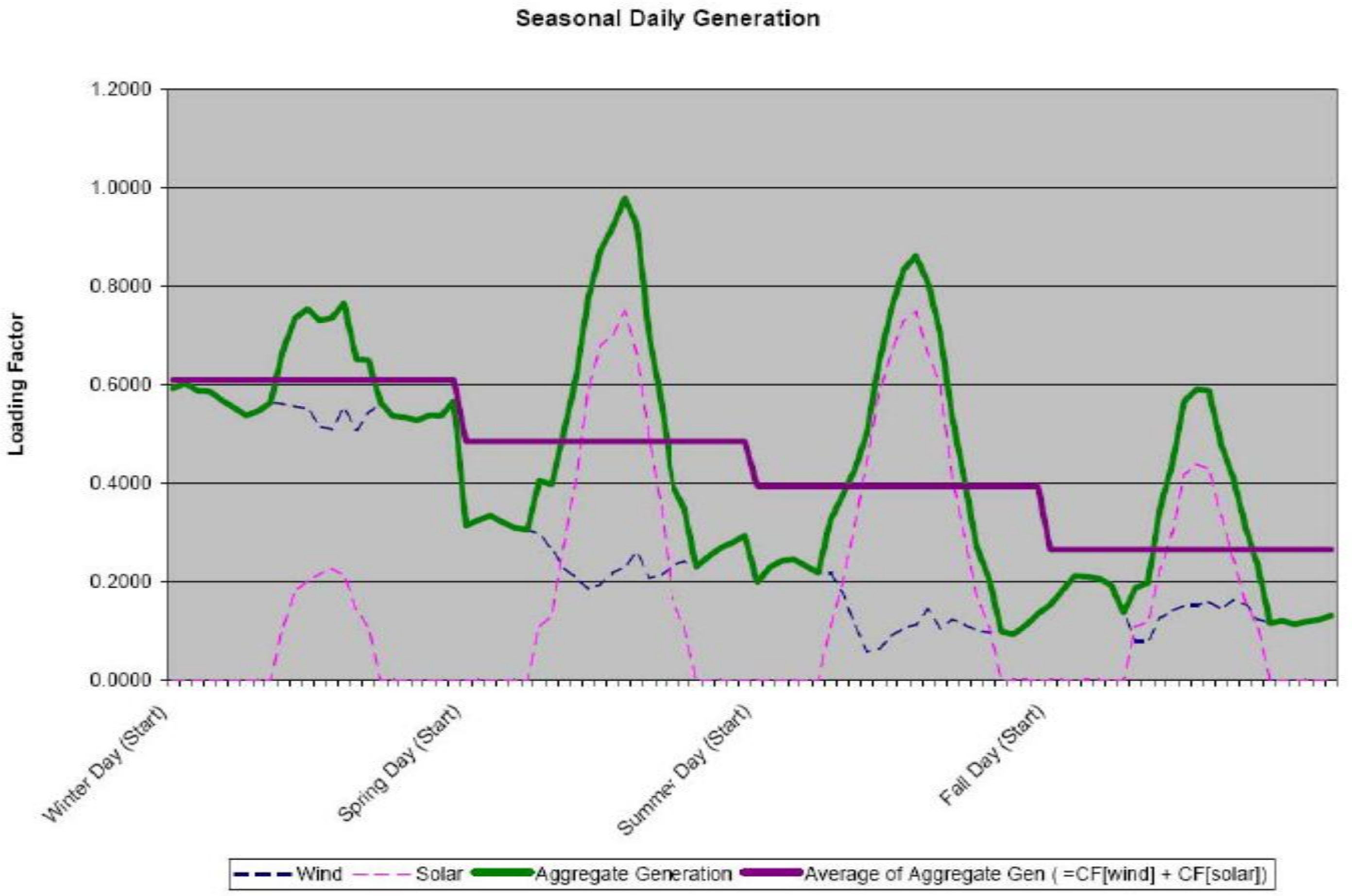
# Benefits of Diversity and Distributed Resources




 Source: R. Seethapathy, Hydro One Presentation to the Ont Smart Grid Forum

# A Signature Visionary Project : Affordable Solar for the Masses

- Low-cost renewable energy critical
- Solar energy is part of the answer
- New technologies will make solar energy more affordable
- Project aims to bring nano-based technologies out of the lab, to make a difference in the world



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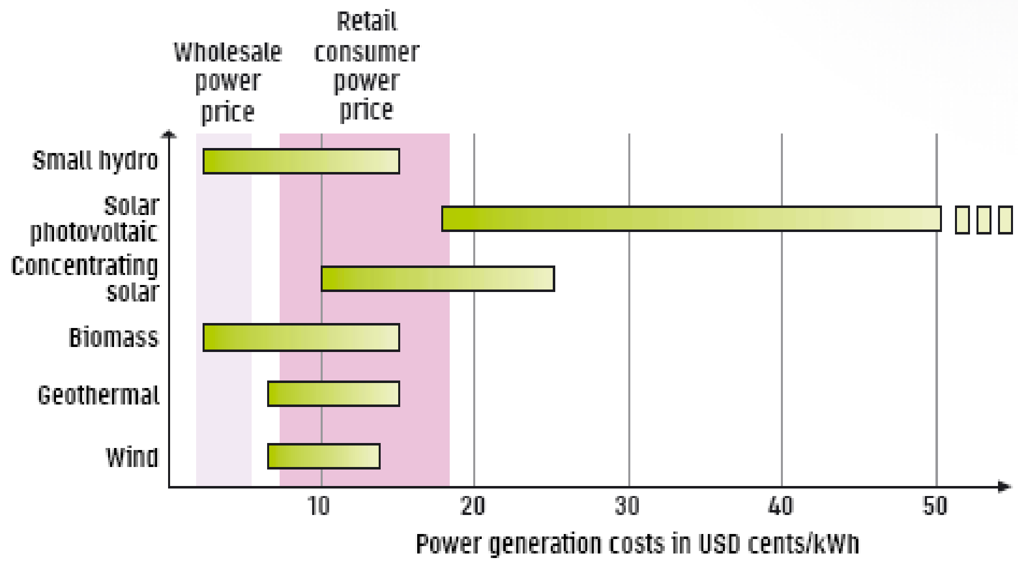
# Affordable Solar?

**Mission is a formidable challenge to get**

- **Below grid parity**
- **Affordable for the masses**
- **Nano-based > 50% efficiency**
- **Obviate expensive grid infrastructure**



# About CAPDS
## Centre for Advanced Photovoltaic Devices and Systems

### The Facility

- 14,000 $ft^2$ facility entirely dedicated for PV research
- Consists of several state-of-the-art laboratories
  - PV METROLOGY AND CHARACTERIZATION LAB
  - NANO-PHOTOVOLTAIC LABORATOTY
  - CLEANROOM FACILITY FOR DEVICE PROTOTYPING
  - THIN-FILM AND ELECTROCHEMISTRY LAB
  - HIGH TEMPERATURE PROCESSING LAB
  - SILICON CRYSTAL GROWTH LAB
  - INGOT AND WAFER PROCESSING LAB
  - SCREEN-PRINTING LABORATORY
  - HIGH-THROUGHPUT PROCESS FACILITY
  - MODULE LAMINATION FACILITY
  - COMNPUTATION AND SIMULATION LAB

http://www.capds.uwaterloo.ca

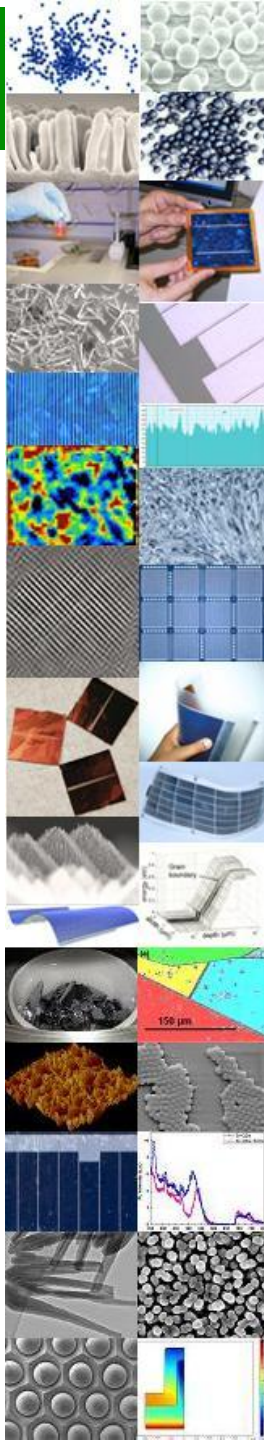
# About CAPDS
## Centre for Advanced Photovoltaic Devices and Systems

### Research Activities

- GROWTH OF BULK SEMICONDUCTOR CRYSTALS
- MATERIAL IMPROVEMENT TECHNIQUES
- ADVANCED THIN FILMS FOR PV DEVICES
- PHOTOVOLTAIC DEVICE DESIGN AND SIMULATION
- DEVICE FABRICATION TECHNOLOGIES
- NANO-STRUCTURE FORMATION (TOP-DOWN AND BOTTOM-UP)
- NANO PHOTOVOLTAIC DEVICE DESIGN AND FABRICATION
- TECHNOLOGY SCALE-UP AND HIGH THROUGHPUT PROCESSES
- ADVANCED LAMINANT MATERIALS AND MODULE ARCHITECTURES
- BACK-END ELECTRONICS
- HEALTHA ND SAFETY EFFECTS OF NEW TECHNOLOGIES

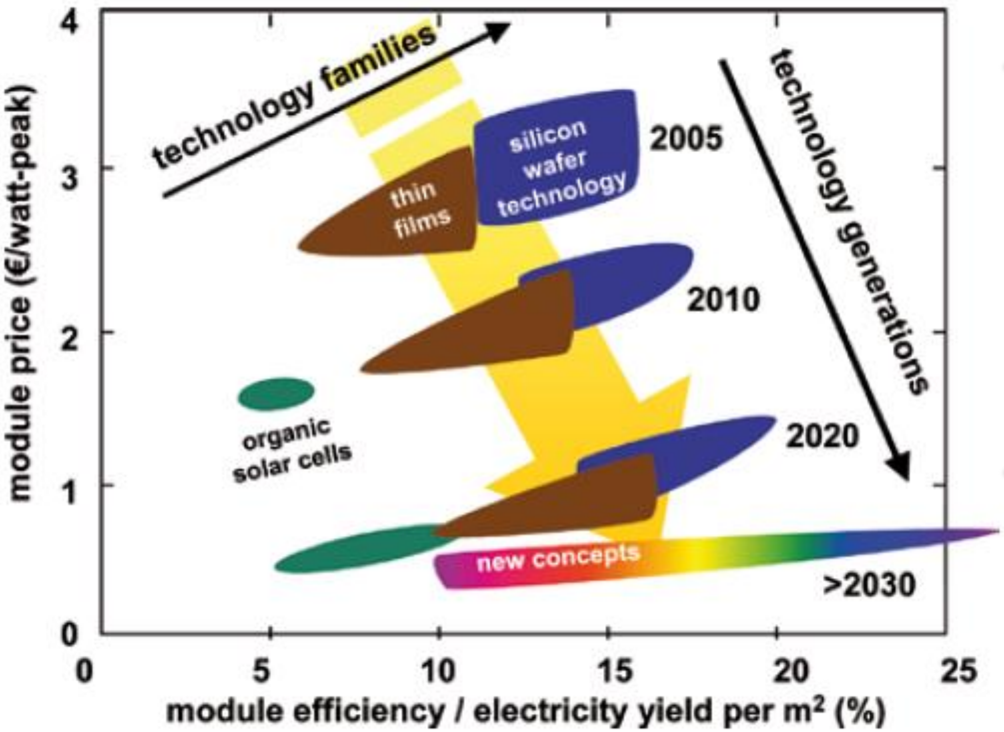
CAPDS

http://www.capds.uwaterloo.ca



# Technology Needs and Directions for Future PV

(W. Hoffmann, Schott Solar)




Technology Improvements

Innovation

Fine-tuning

New Concepts

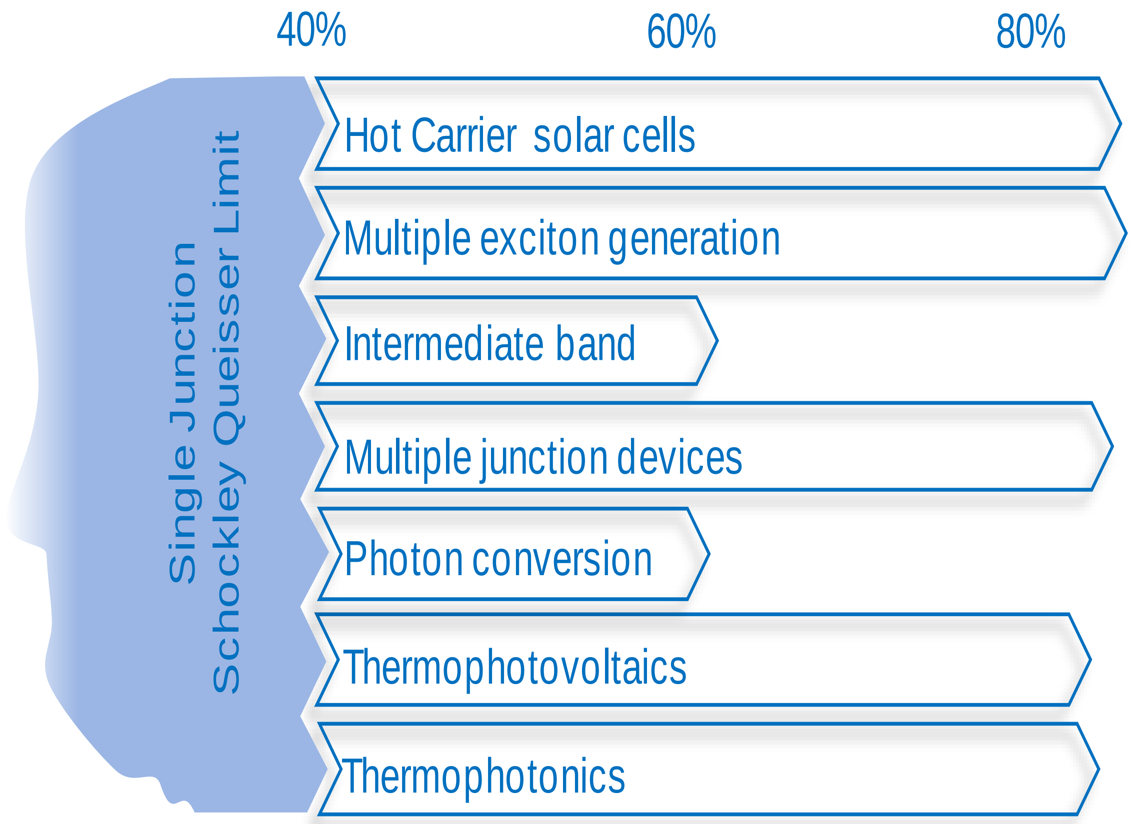
Nanotechnologies

Ultra-high efficiencies

# Pathways for Very High Efficiency PV Devices

- Theoretical predictions of device performance remain scientifically unchallenged

- Breakthrough research in materials and device technology is necessary for practical realization of high performance PV devices



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# Technology Goals and Research Directions

Crystalline Silicon Technologies

| | 2010 - 2015 | 2015 - 2020 | 2020 - 2030 |
|---|---|---|---|
| Module Efficiency (commercial) | Mono Si: 21%<br>Multi Si: 17% | Mono Si: 23%<br>Multi Si: 19% | Mono Si: 25%<br>Multi Si: 21% |
| Silicon Consumption | < 5 grams /watt | < 3 grams / watt | < 2 grams / watt |

## Research Thrust Areas:

- New approaches for Silicon feedstock processing
- Advanced wafering (and wafer equivalent) technologies
- Surface passivation and metal contacting
- New device architecures optimized for high performance

# Technology Goals and Research Directions

Thin Film Technologies

| | 2010 - 2015 | 2015 - 2020 | 2020 - 2030 |
|---|---|---|---|
| Module Efficiency (commercial) | Thin film Si: 10%<br>CIGS: 17%<br>CdTe: 12% | Thin film Si: 10%<br>CIGS: 17%<br>CdTe: 12% | Thin film Si: 10%<br>CIGS: 17%<br>CdTe: 12% |
| Manufacturing | High deposition rates | Management of Toxic materials | Large production units<br>Recycling options |

Research Thrust Areas:

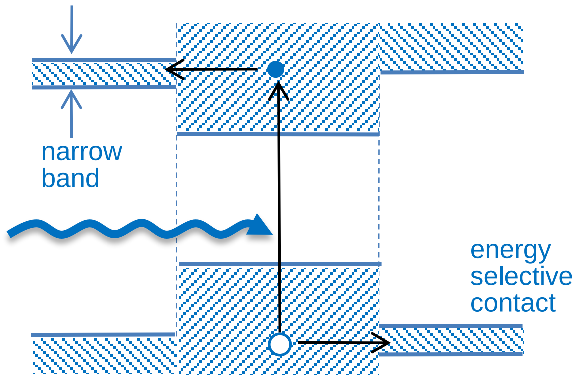
- Large area deposition of thin films with high controllability
- Improved substrate materials and transparent conductive oxides
- Improved cell structures (double, triple junctions)
- Advanced material concepts and synthesis

# Technology Goals and Research Directions

Waterloo Institute for Sustaina

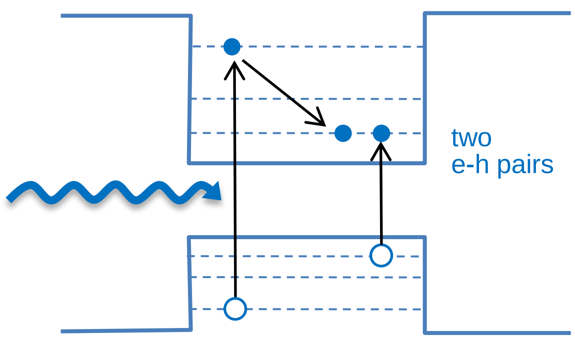
## New Concepts: Nano Technologies

### Hot-carrier solar cell concept




- Carriers are collected before they thermalize.
- Narrow bands for carrier extraction
- 66% (one-sun) and 85% (xsuns) theoretically possible.

### Multiple excitons concept




- Extra e-h pairs are created by impact ionization.
- Carrier relaxation rate made slower
- 66% (one-sun) and 85% (xsuns) theoretically possible.

Nanowires

Quantum dots

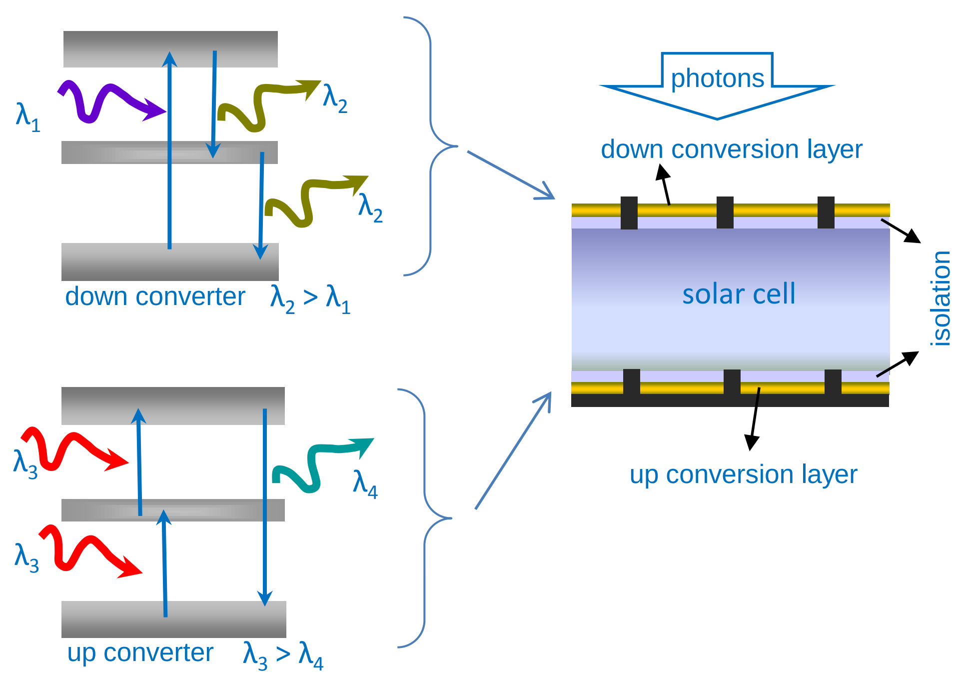
Materials with engineered properties

# Technology Goals and Research Directions



## New Concepts: Nano Technologies

Photon conversion




Nanostructured materials with tailored absorption / emission properties.

A conversion efficiency of 63% is theoretically possible under concentration

# CAPDS R&D Approaches

*"Mature" Technologies*

Silicon Wafer Technologies

Thin film Technologies

- Crystal Growth
- Thin-film Deposition
- Material Improvement
- Improved Device Design
- Fine-line Screen-printing
- Module Technologies

**Short - to - Medium Term**

The "Middle-ground" Approach

Some advanced concepts deployed on traditional technology platforms

- Spectral-engineering
- Plasmonic Thin-films
- Smart Modules

*"Future" Technologies*

Nanotechnologies: Engineered materials & Novel device architectures

- Multiple Exciton Devices
- Hot carrier PV Devices
- Intermediate Bandgaps

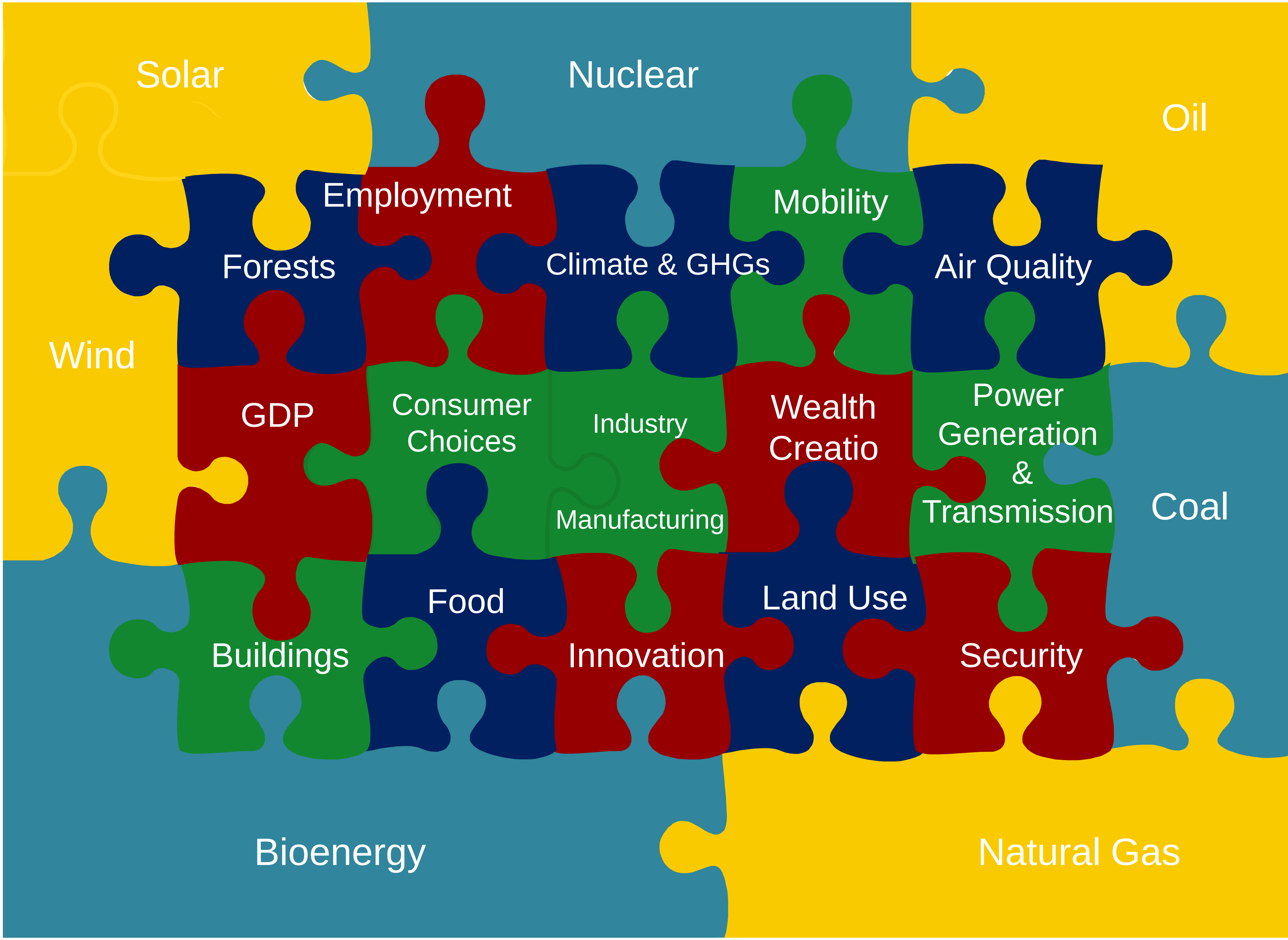
**Long Term**

# Requirements for Success- A Mission Focus and Tripartite Partnership

- **Strong academic leadership and commitment**
  - University of Waterloo
  - Existing facilities- Centre for Advanced Photovoltaic Devices
  - Multiple global level academic collaborators
- **Industry**
  - Commercialization focus
  - Business and Industry Partners with long view
- **Governments**
  - Strong endorsement and commitment to policy direction
- **Funding and human resources**

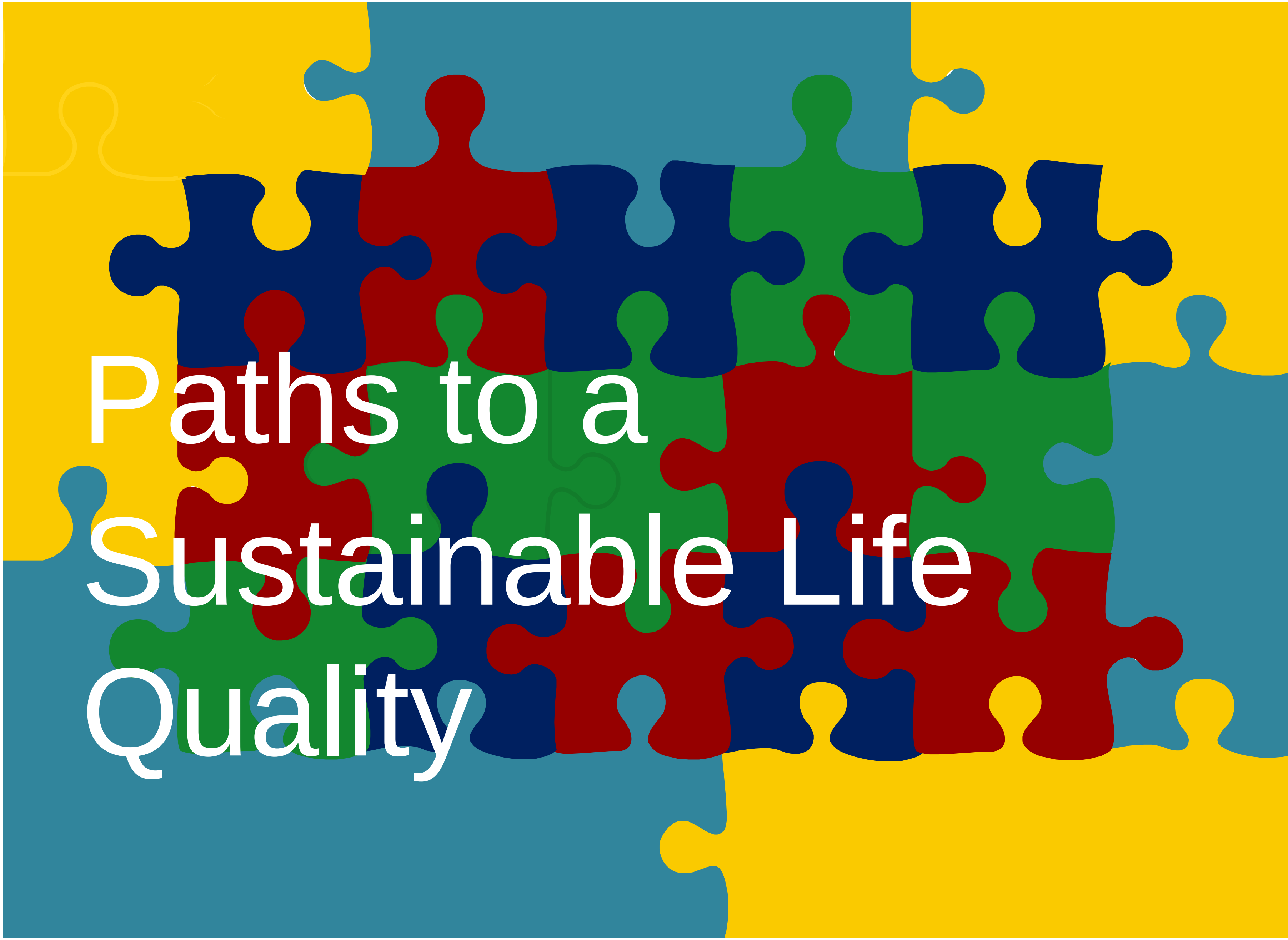
# Guideposts that may shape future directions

1. Energy flows through the global economy are massive: huge inertia
2. Scale and complexity of change suggests transition to a low GHG economy will take a long time
3. Growth, development, energy demand and environmental performance are intricately linked
4. Historical trends away from consumption of primary fuels directly to electricity will continue
5. The power sector will be characterized by a low carbon intensity
6. The electricity sector as the "cleaning agent" of the transport sector is an idea that is only beginning to emerge.
7. A balanced mix: renewables, nuclear, efficiency gains, conservation and clean(er) fossil resources would allow for sustainable prosperity and good environmental performance.


Solar
Nuclear
Oil
Employment
Mobility
Forests
Climate & GHGs
Air Quality
Wind
GDP
Consumer Choices
Industry
Wealth Creatio
Power Generation & Transmission
Manufacturing
Coal
Food
Land Use
Buildings
Innovation
Security
Bioenergy
Natural Gas

# Summary

- **Compelling global need for a non-carbon based source of high quality energy**
    - Breaking the efficiency and cost barrier for solar is the mission
- **Global dimension of energy poverty is an even larger and deeper social and economic problem**
    - Affordable solar has the potential to change the game
- **Advancement of human development and quality of life is a profound obligation for all**
    - Business, industry, governments, academy


Paths to a
Sustainable Life
Quality

# Technology Innovations

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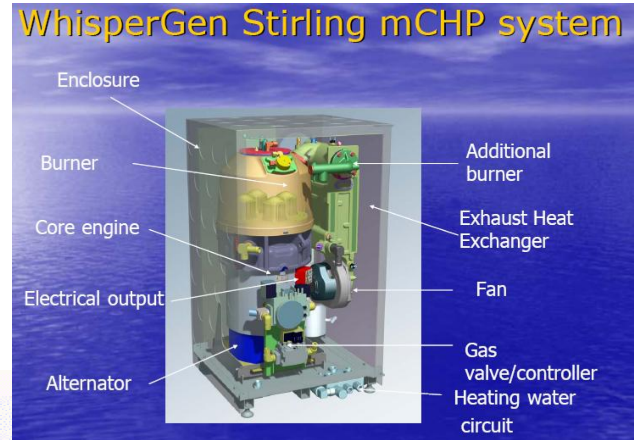
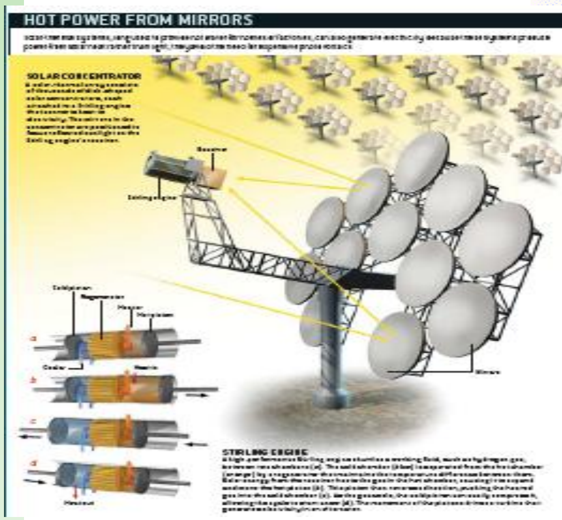
- Charges in under 1 minute.
- Range: 15 km at 40 km/h.
- Cold weather testing in Sapporo next month.
- Uses 10% less energy than existing streetcars.




re 5: Transportability of 5.2-MW turbines to SRP substations

Turbines's 5.2-MW turbines and balance-of-plant equipment will be transportable by allowing Salt River Project to move the units to areas with the greatest distribution n need.

Source: David Gauntlett [25]

# The Waterloo Institute for Sustainable Energy (WISE)

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Waterloo Institute for Sustainable Energy
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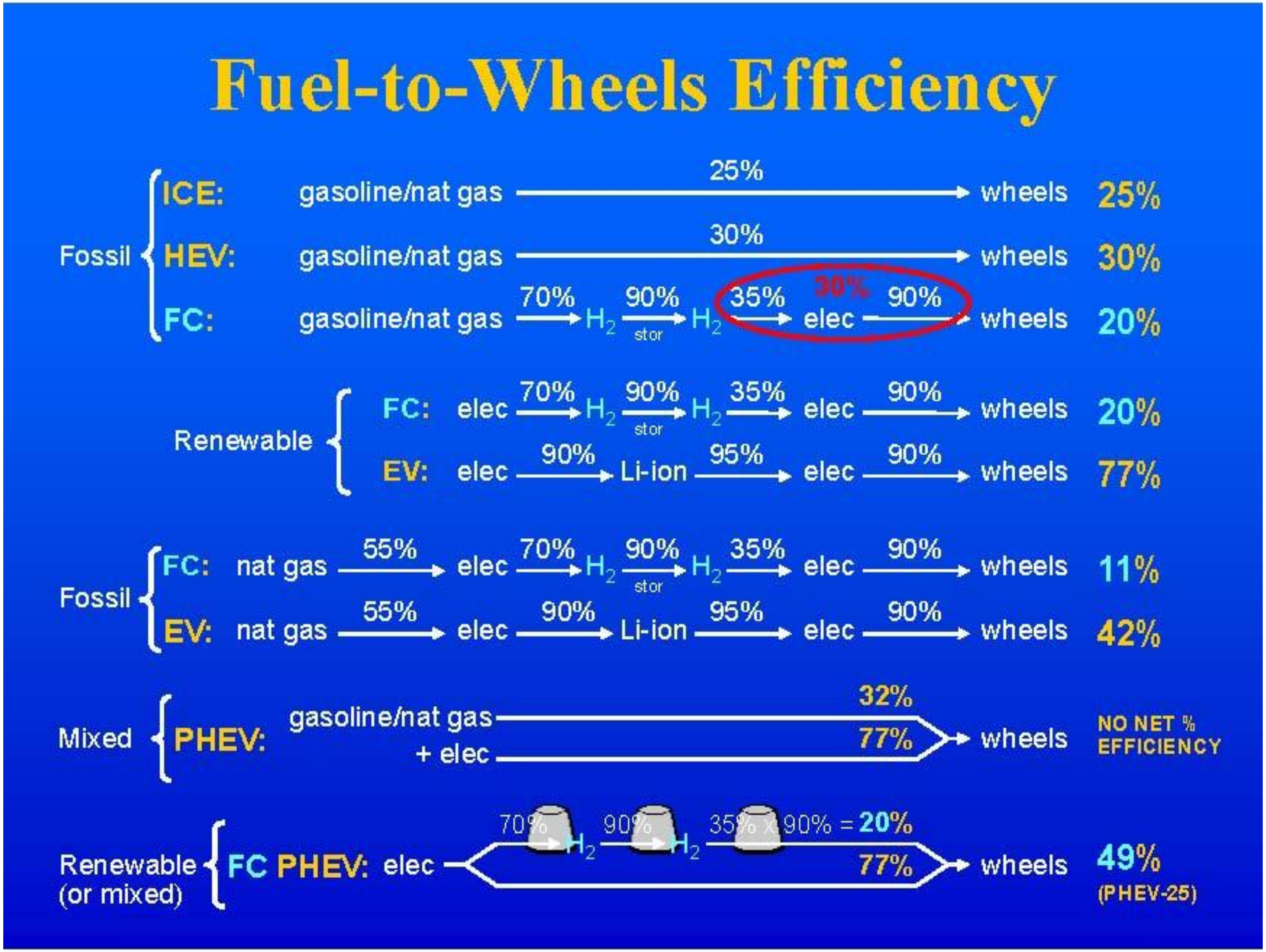
# Background Material

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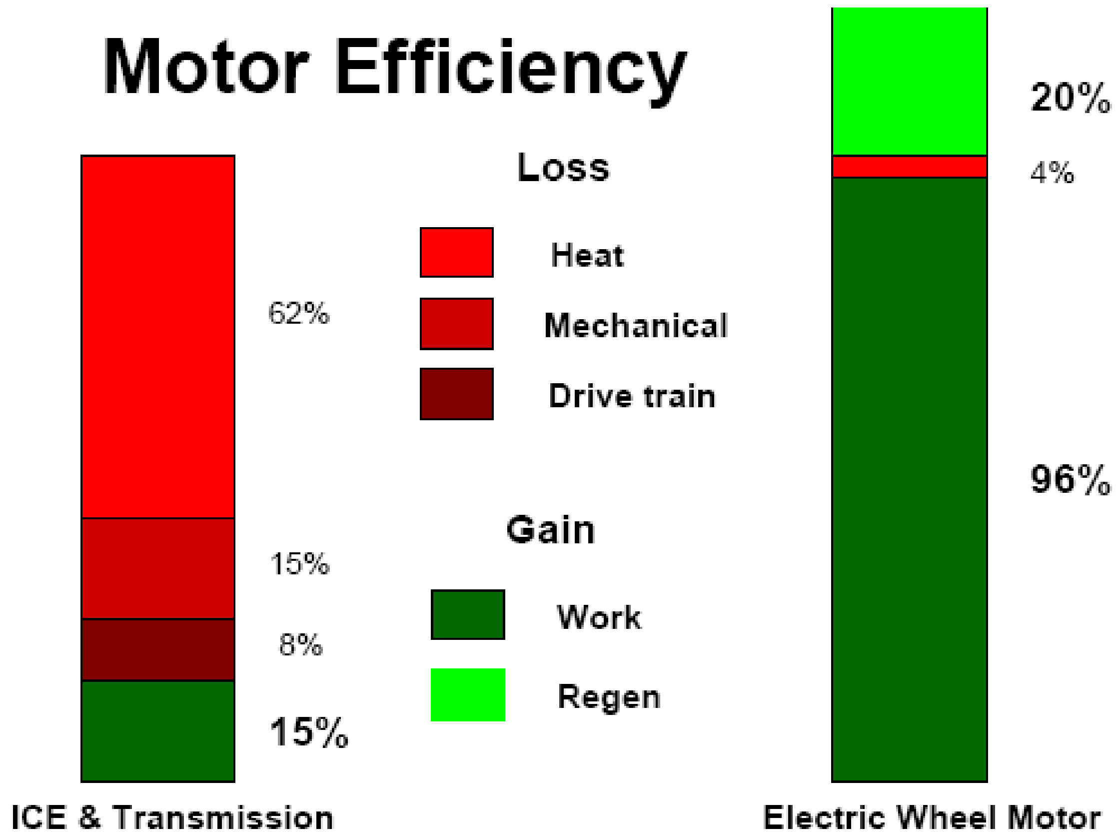




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# Comparison of Electric Vehicle and Hydrogen

## Cost of Using Hydrogen

| 2003 Honda FCX | |
|---|---|
| Miles per kilogram of hydrogen<br>51 city 48 hwy<br>Annual Fuel Cost: **$1515*** |  |
| EPA Air Pollution Score | Best 10 (0 – 10) |
| Range | 170 miles |
| Fuel | Hydrogen |
| Fuel Cell | Polymer Electrolyte Membrane |
| Motor | 60 kW DC |
| Energy Storage Device | Ultracapacitor |

*Annual fuel cost is estimated assuming 15000 miles of travel per year (55% city and 45% highway) and a fuel cost of $5.05 per kilogram of gaseous hydrogen.

**2003 Toyota RAV4 EV**

**Electric Vehicle**

Possible Tax Incentives

Use your Gas Prices

Switch to Metric units

| Fuel Economy | |
|---|---|
| Fuel Type | Electricity |
| Energy Consumption(city) (kW-hrs/100 miles) | 27 |
| Energy Consumption(hwy) (kW-hrs/100 miles) | 34 |
| MPG (city) | 125 |
| MPG (highway) | 100 |
| MPG (combined) | 112 |
| Annual Fuel Cost @ 8¢/kWh | $362 |

| | | | |
|---|---|---|---|
| 2003 Honda Civic Gasoline Cost | $684 | 2003 RAV4 2WD Gasoline Cost | $860 |
| 2003 Honda Civic Gas Hybrid Cost | $484 | | |

- Hydrogen cost is worse than its efficiency!
- Electrolysis twice as costly as natural gas!
  - $3,000 per year for hydrogen Honda FCX.

Manitoba Hydro