Opportunity Analysis for Recovering Energy from Industrial Waste Heat and Emissions

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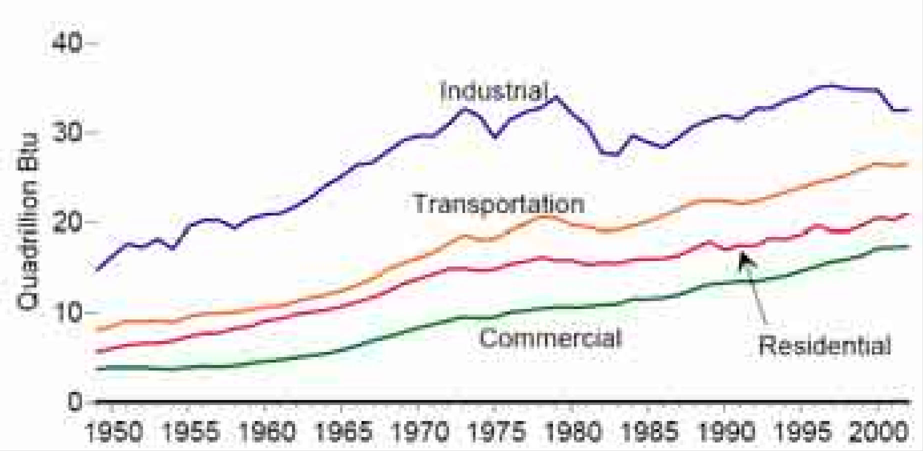
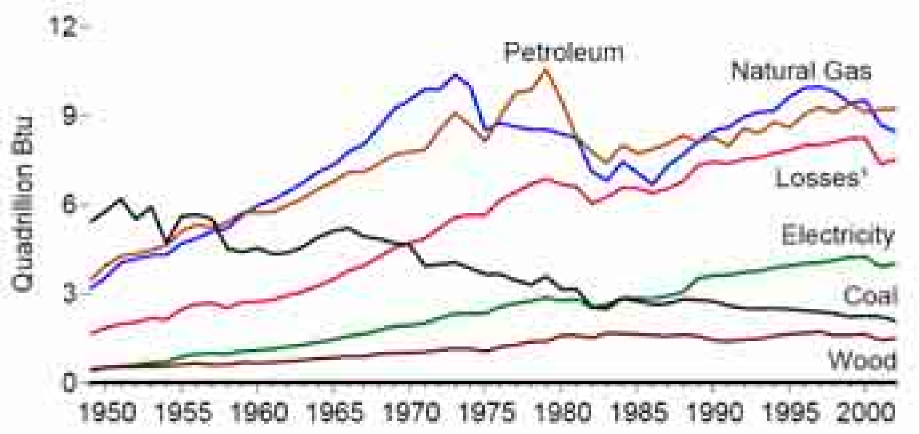
Introduction

- United States Industry has a wide spectrum of emissions and major sources of waste heat
- This presentation discusses:
  - Emissions
    - variety of chemical emissions with residual fuel value
    - results of a survey of industrial emissions to quantitatively identify the amount of chemical energy available in these emissions
    - discussion of the limitations of this survey
    - concepts to recover this energy and materials R&D needs
  - Waste Heat
    - discusses the amount of energy within industrial waste heat, and potential recovery methods
  - Opportunities- Barriers-Pathways
    - Materials needs and challenges – recovery challenges
- Summary

U.S. Industrial Energy Consumption

- U.S. Industry is a large consumer of energy
- U.S. Industry is heavily dependent on petroleum and natural gas





Data Source: Energy Information Administration Annual Energy Review 2002: www.eia.doe.gov/aer

Industrial Emissions Survey

- Non-combustion related process emissions
  - Aluminum
  - Chemicals
  - Glass
  - Natural Gas
  - Petroleum
  - Steel
  - Landfill
  - Mining
  - Forest Products
  - Metal Casting
  - Agriculture
  - Semi-conductors
- Combustion related emissions
  - Stationary fossil fuel combustion

Approach

- Source: EPA US GHG Emissions Inventory 1990-2001
- Data cross-checked with other sources such as DOE's Energy Information Administration
- Breakdown of energy and process related emissions done for each industry (when data available)
- Energy content of emissions computed using heat of combustion at Standard Temperature and Pressure (STP)

Primary Sources and References

- EPA, U., *Inventory of US Greenhouse Gas Emissions and Sinks*. 2003, US Environmental Protection Agency.
- EIA, U., *Emissions of Greenhouse Gases in the United States 2002*. 2003, Energy Information Administration: Washington, D.C.
- EIA, U., *Annual Energy Review*. 2003, Energy Information Administration.

Sectors with high energy contents for emissions

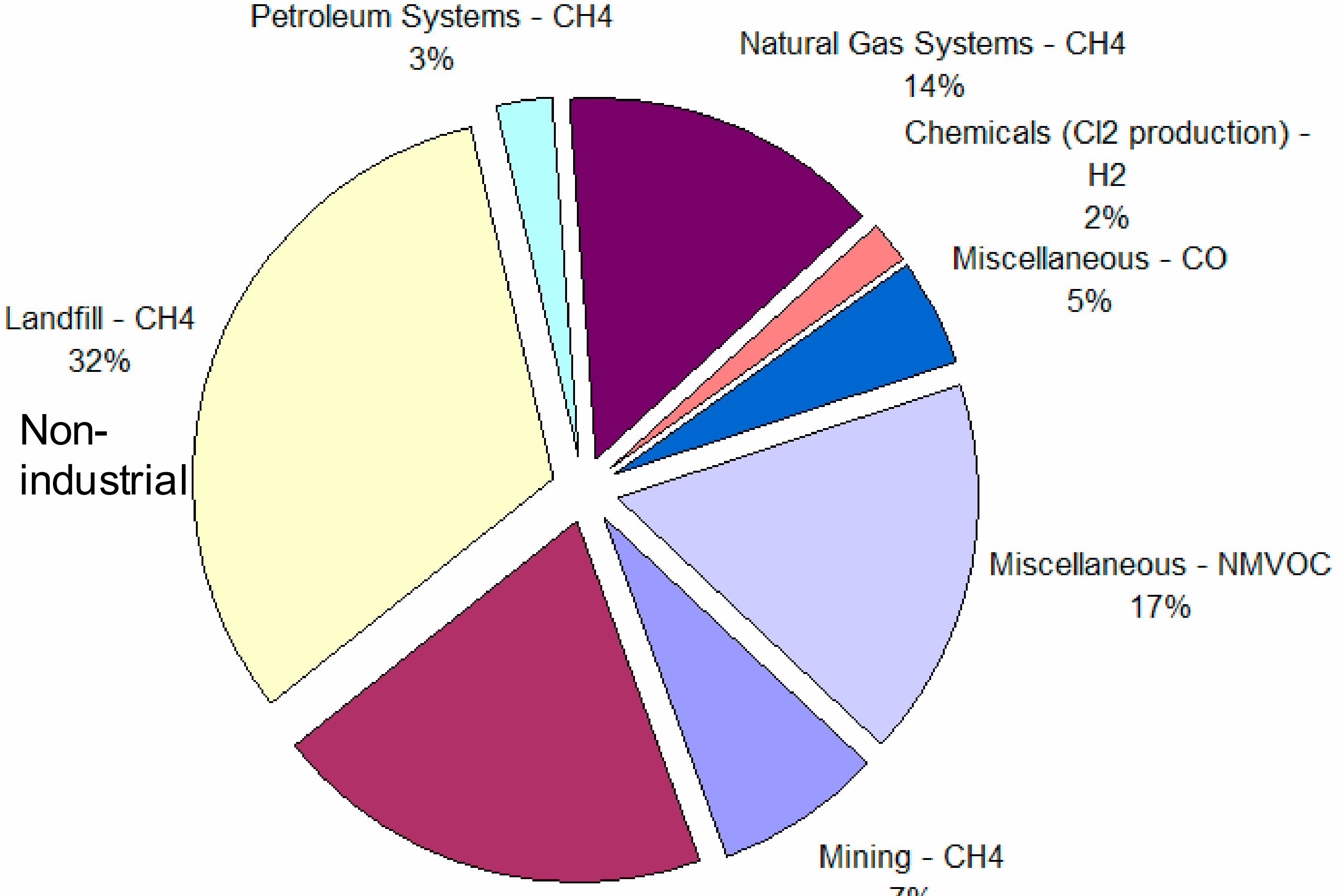
- Landfills (methane) – ~20% of emissions are captured
- Mining (methane)
- Agriculture (methane)
- Natural gas systems (methane)
- Petroleum refining – in addition to methane emissions, significant opportunity exists in capturing energy from H2S generated from hydro-treatment of evolved SOx.
- Chemicals (chlorine production) (Hydrogen)
- CO and NMVOCs also emitted from various industries
  - Iron and Steel, Petroleum Systems, etc.

Energy Content in Emissions

Industry	Gas	Emissions (Tg)	Energy (PJ)
Mining	CH_4	2.89	161
Agriculture	CH_4	7.72	430
Landfill	CH_4	12.53	698
Petroleum Systems	CH_4	1.01	56
Natural Gas Systems	CH_4	5.59	311
Chemicals (Cl_2 production)	H_2	0.29	42
Miscellaneous	CO	10.3	104
Miscellaneous	NMVOCs	7.27	368
Total Energy			**2107 PJ**

Total = 2,000 Trillion BTU

Energy Content in Emissions



Total = 2,000 Trillion BTU

Emissions from fossil fuel combustion

- In 2001, 5561 Tg CO_2 eq emitted from fossil fuel combustion.
- The contribution of industrial fossil fuel combustion was 938 Tg CO_2.
- *Fossil fuel combustion contributes 70% of emissions from industry*
- Significant uncertainty in emissions of CH_4, CO, NMVOCs from fossil fuel combustion
- Limited data verified by PNNL using emission factors for CH_4 and energy used within each industry.
- *Emissions of CH_4, CO, NMVOCs from fossil fuel combustion was negligible – using our conservative method*
- The report energy content is *process* related emissions
- Investigated various technologies for utilization of CO_2 emissions from fossil fuel combustion

Other Potential Emission Recovery Opportunities – not quantified

- Aluminum
  - aluminum reduction process emits CO, CO_2, SO_2. Opportunity exists for recovery of energy from CO.
  - Electrolytic reduction of alumina highly energy-intensive. Process integration with other sectors that evolve energy containing gases would decrease electricity needs
- Iron & Steel, Glass, Cement
  - do not appear to produce energy containing emissions – conflicting data
  - CO_2 emitted can be captured and utilized
- Chemicals
  - Process integration can be effective in this sector. Setting up networks of various chemical production in which a by-product of one process can be used as feedstock for the other is an example of such an integration.
- Petroleum Refining
  - The fluid cracking unit in the refinery emits SO_x and NO_x. These emissions are hydrotreated to yield H_2S, from which energy can be captured.
  - H_2S produced in large amounts during desulfurization of fossil fuels and in coal gasification. There is significant energy in H_2S. H_2S can be converted to H_2 in a Na-S type cell, and the generated H_2 can be fed to a fuel cell.

Process Integration & Optimization

- Use of by-product from one process as feed to another process. Ideally, one can have a network of several such processes.
  - HCl by-product in vinyl chloride production used as raw material in oxy-chlorination of ethylene.
- By-products from chemical processes also can be used as feedstock in other industries (HCl in steel making) and vice-versa (HCl from semi-conductor manufacturing)
- Multi-industry network –
  - example: oil refinery, sulfuric acid plant, pharmaceutical manufacturing, coal-burning power plant, fish farm, gypsum board manufacturer form an industrial network in Kalundborg Denmark.
  - Steam, gas and cooling water exchanged between power plant and refinery. Waste heat from power plant used for residential heating and in fish farm.
  - Ash from power plant used for cement manufacture
  - $CaSO_4$ from power plant sent to gypsum board facility
  - Refinery sends hot liquid sulfur from desulfurization of crude oil to sulfuric acid manufacturer

GHG (Tg CO2 Eq.) allocated to various sectors

Sector	1990	2001
Electricity	1862	2298
Transportation	1526	1867
Industry	1423	1316
Agriculture	488	526
Residential	335	379
Commercial	472	497
Total	6106	6883

Utilization of CO_2

- Most of GHG emissions (> 70%) from industry are CO_2. CO_2 can be utilized as follows:
  - Tri-reforming a mixture of CO_2, CH_4 and H_2O to yield H_2, which can be fed to a fuel cell. Avoids expensive separation step for flue gases that contain CO_2/CH_4 mixture. Avoid carbon formation by using water.
  - Use of di-electric barrier discharge to convert CO_2/CH_4 mixture to synthesis gas with various H_2/CO ratios depending on CO_2/CH_4 ratio in flue gas.
  - Pyrolysis of hydrocarbons for manufacture of ethylene and propylene.
  - Use of CO_2 as feedstock using transition metal-catalyzed reactions to manufacture esters, amides, alcohols, polycarbonates.
  - Reaction of CO_2 with NH_3 to form urea
  - Gasification of carbon with CO_2 to form energy containing CO.
  - Photocatalytic reduction of CO_2 with water to form CH_4 and CH_3OH

Industrial Waste Heat Recovery Opportunity

- Energetics Inc. recently performed a study that included waste heat recovery opportunities
  - *Energy Use, Loss and Opportunities Analysis: U.S. Manufacturing & Mining*, Energetics, Inc and E3M, Inc for the U.S. Department of Energy, November 2004.
  - Quantified major sources of heat rejected to the atmosphere
  - Studied most energy intensive U.S. industries
- We are summarizing the largest opportunities to recovery the waste heat presented by Energetics.

Industrial Waste Heat Recovery Opportunity #1 (from Energetics)

- **Waste heat recovery** from gases and liquids in chemicals, petroleum, and forest products, including hot gas cleanup and dehydration of liquid waste streams
  - ~7 quads of waste heat above 75F conservatively estimated
  - 851 Trillion BTU recoverable
    - ~65% from exhaust gases (combustion related)
    - ~35% from low/medium temperature liquids (process related)
- Waste heat from waste steam, exhaust and flue gases, flares, hot water and radiation heat losses

Industrial Waste Heat Recovery Opportunity #4 (from Energetics)

- **Heat recovery from drying processes** - chemicals, forest products, food processing
  - ~2 quads of waste heat conservatively estimated
  - 217 Trillion BTU post-process energy recoverable

Industrial Waste Heat Recovery Opportunity #10 (from Energetics)

- **Waste heat recovery** from gases in metals and non-metallic minerals manufacture (excluding calcining)
  - ~1.5 quads of waste heat conservatively estimated
  - 235 Trillion BTU post-process energy recoverable

Opportunities

- ~10 Quads of energy emitted as waste heat from U.S. Industries

~1.4 Quads of energy emitted with residual, chemical fuel value from industrial process emissions (w/o Landfill)

Barriers

- Economical methods to recover energy from waste heat and emissions
  - Emissions and waste heat is distributed
  - Recovery device efficiency is critical
- Awareness of the opportunities in industry

Pathways

- RD&D of economical energy recovery systems
  - High-efficiency, low-cost devices to recover waste heat
  - High-efficiency, low-cost devices to recover energy from industrial emissions
- Develop Materials and technology to mitigate waste heat energy loss (refractory and insulation)
- Education regarding opportunities to industry

Industrial Emissions Recovery Materials and Process Challenges

- Barrier
  - Most chemicals with fuel value are dilute
  - Need for separations and pre-concentration schemes
- Pathways
  - Material for Separations
  - Materials/technology for collection and pre-concentration
  - Fuel-flexible, impurity tolerant fuel cells

Example Techniques for Emissions Energy Recovery

- High temperature fuel cells such as SOFC or MCFC ideal for biogas
- Conversion of municipal solid waste to biomass and high value chemicals. Biomass can be converted in biorefinery to ethanol.
- Plasma used to convert wastes to valuable products such as roofing tiles, insulating panels and H2 rich gas for use in fuel cell
- Ford's technology to capture energy from paint using a regenerative thermal oxidizer.
- Ford's technology to convert VOCs from paint (after concentration in a fluidized bed) to hydrogen in a reformer. H2 fed to SOFC. This technology can be used to convert VOCs from various industries to a H2-rich gas stream.

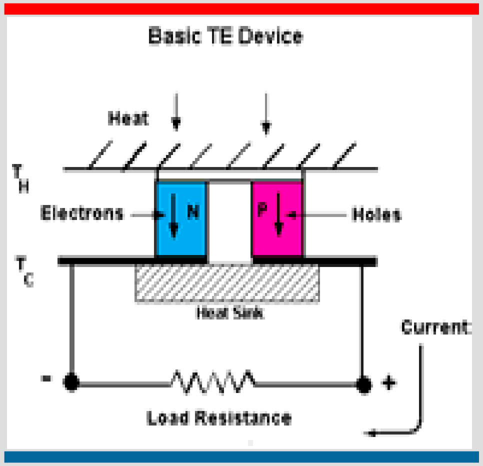
Industrial Waste Heat Recovery Materials and Process Challenges

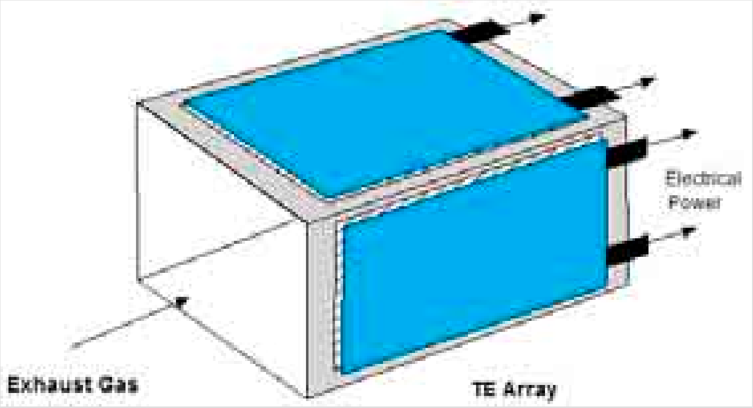
- Barrier:
  - Waste heat is distributed. We need a cost effective way to recovery this distributed energy.
- Pathways:
  - High-efficiency heat transfer (heat exchange, heat pipe)
  - Convert heat to electricity
    - thermoelectric, piezoelectric, TPV
  - Combined heat and power (CHP)
  - Improved refractory materials

Thermoelectric Generators for Waste Heat Recovery

- Energy Savings 135 T BTU/year
- Large Quantities of Thermal Energy are Available From Waste Energy Streams
  - glass, steel, alum, chem
- Generation of Electrical Power with Therrmoelectrics Will Involve Placing TE Arrays on the Sides of Waste Energy Ducts

- Key TE Material Challenges:
  - Increase TE Efficiency
  - Scale-Up Fabrication Process to Reduce Cost





Summary

- We identified approximately 2,000 Trillion Btu of chemical fuel value contained in emissions – 1400 TBTU Industrial
  - We believe this is a conservative estimate
  - Recovering 10% would yield 140 TBTU
  - 70% of total emission are combustion related – no residual value
    - Insufficient data to truly assess incomplete combustion
  - Most chemical fuel value is contained in the 30% of emissions from industrial processes
- Energetics has recently identified Energy Savings through "Waste Heat and Energy Recovery" of 1,831 Trillion Btu
  - Possibly 10 quads of energy available to recover from waste heat
- There appear to be materials and process R&D required to realize the economic recovery of these waste emissions and waste heat.