

Nuclear Renewable Oil Shale System (NROSS)

Making Oil Shale the Fossil Fuel with the Lowest Greenhouse Impact per Liter of Diesel or Gasoline While Improving Economics

34th Oil Shale Symposium; Boulder, Colorado

Charles Forsberg and Daniel Curtis

Massachusetts Institute of Technology

77 Massachusetts Ave., Room 24-207A, Cambridge, MA 02139

Tel: 617-324-4010; Email: cforsber@mit.edu; djcurtis@mit.edu;

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Abstract

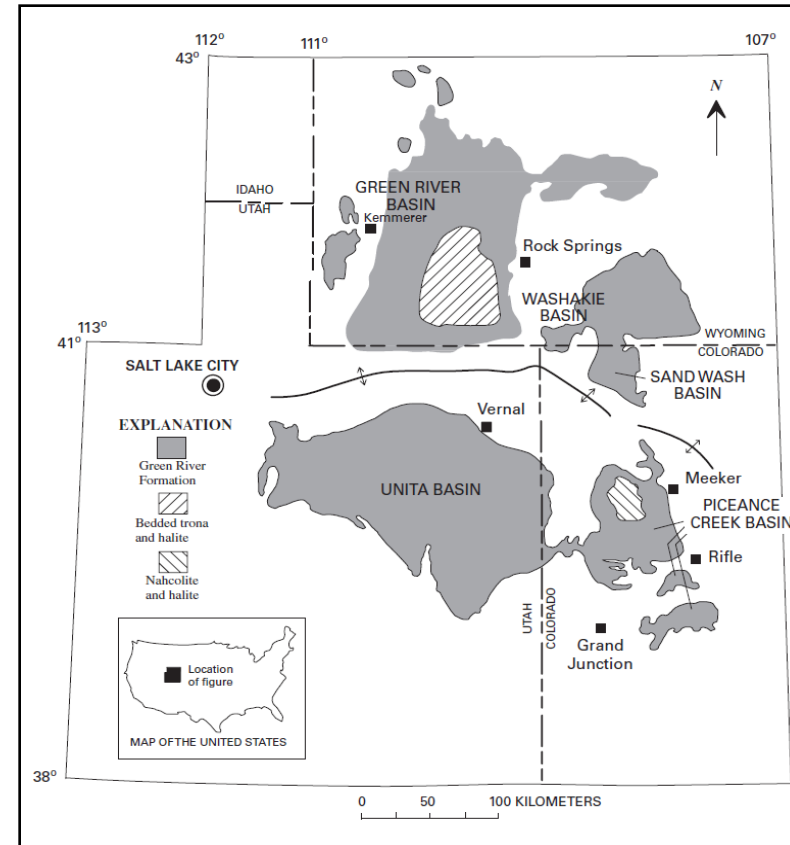
A nuclear renewable shale oil system (NROSS) is proposed with three goals: (1) lowest greenhouse gas emissions of any fossil fuel per liter of diesel or gasoline, (2) enabling technology for a zero-carbon electric grid for the western United States and other areas (eastern Baltic) with large oil shale (kerogen) reserves, and (3) competitive economics. Light water reactors (LWRs) are built on top of oil shale deposits. Oil shale heating (surface such as Red Leaf or insitu) is accomplished in a two-step process via closed steam lines. Initial Phase-I heating to temperatures between 220 to 270°C is accomplished using steam from LWRs that have peak steam temperatures near 300°C. In the second stage of heating, grid-generated electrically-heated steam is circulated to raise shale temperatures to ~370°C for oil production. The LWRs operate continuously at full power with steam being used for Phase I heating of shale when the price of electricity is low and producing electricity for the grid when the price of electricity is high. At times of low electricity prices, electricity is purchased from the grid for Phase II heating of the shale. This strategy minimizes costs of providing heat for shale oil recovery while maximizing revenue for the nuclear plant.

The strategy minimizes greenhouse gas emissions per liter of gasoline or diesel from shale oil production. It also enables a zero-carbon nuclear renewables electricity grid. In the western U.S. wind has attractive electricity costs in mills per kWh but is uneconomic because one has to have backup gas turbines to provide electricity when wind conditions are low—that kills the economics. NROSS fixes that problem with nuclear power providing variable zero-carbon electricity to the grid when there are low wind conditions. If NROSS oil also receives some of the credit for eliminating greenhouse gases from the electricity grid, the calculated CO₂ releases per liter of fuel are substantially less than from burning those fuels.



The Challenge

- Over 2 trillion barrels of oil in solid kerogen shale in the Western US
- Exceeds total oil produced to date worldwide
- Production methods produce large quantities of greenhouse gases

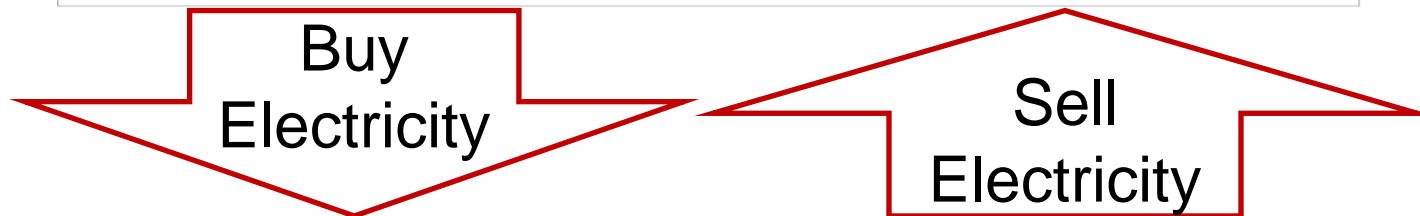
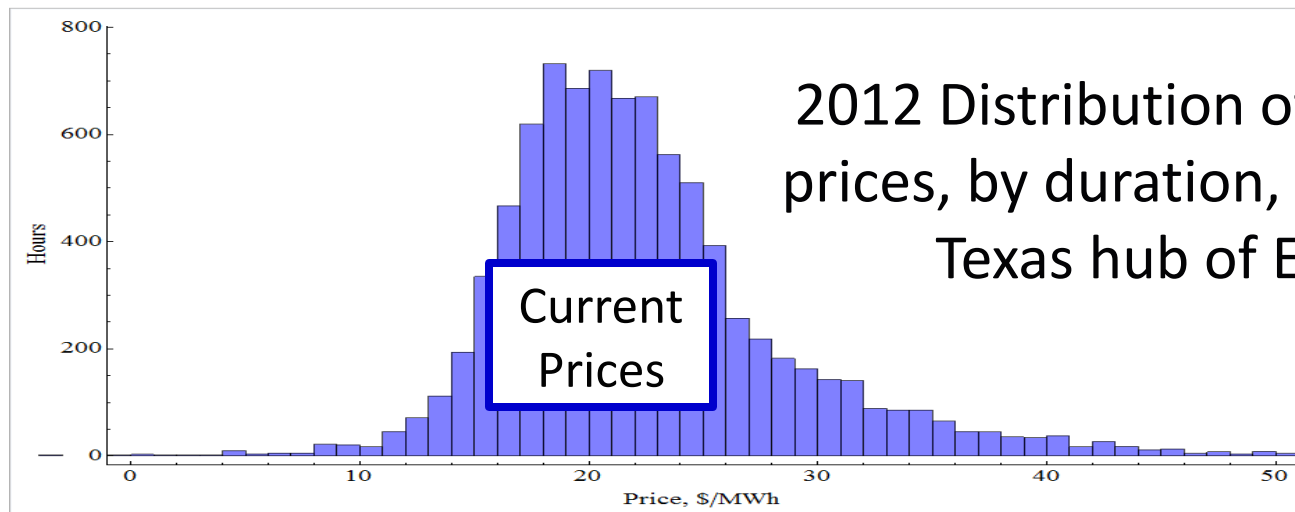


**Concerns about Climate Change & CO₂ Emissions
May Prevent Use of this Mega Resource**

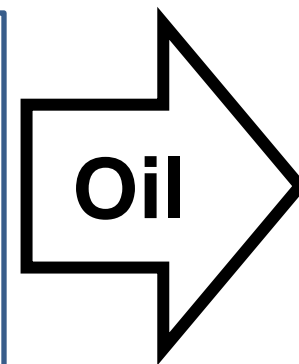
Nuclear Renewable Oil Shale System (NROSS) Goals

- Lowest greenhouse gas emissions of any fossil fuel per liter of gasoline or diesel
- Enable a zero-carbon electricity grid for the mountain west with use of Great Plains wind resources
- Favorable economics
 - Independent of CO₂ tax or cap & trade
 - Economics improves if greenhouse gas constraints

NROSS Integrates Shale Oil Production and the Electricity Grid to Reduce Greenhouse Gas Releases and Improve Economics



NROSS
Low-Carbon-Footprint
Fossil-Fuel Oil

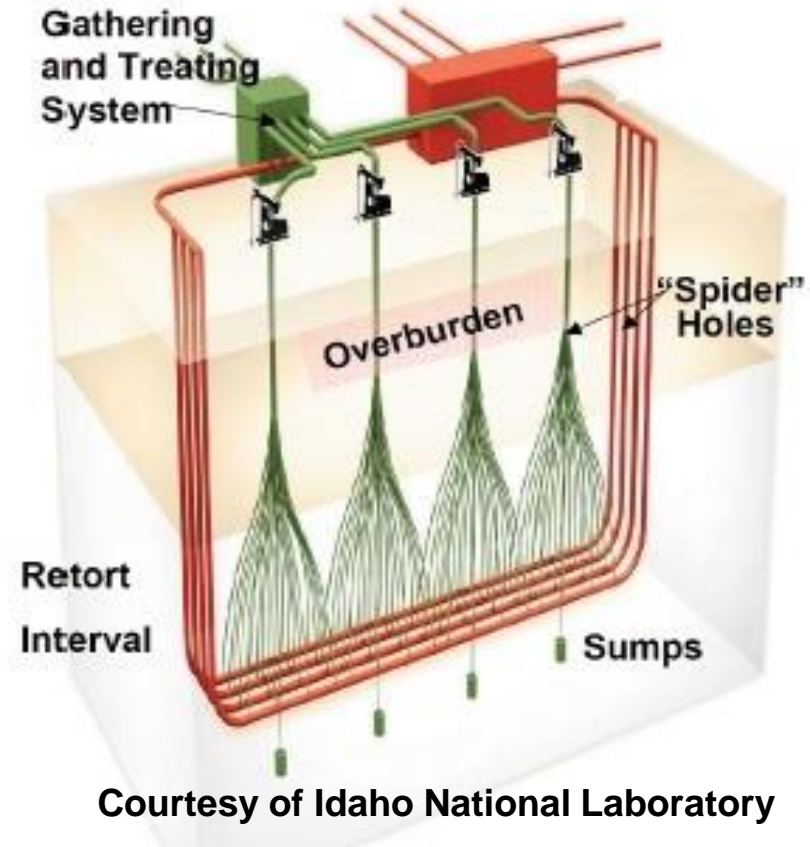


NROSS is a Two Part Story

Oil Shale (Kerogen) Production
Zero-Carbon Electric Grid

Use Heat from Nuclear Reactor For Oil Shale Retorting

- Slow heating kerogen shale over 1 to 3 years
 - Solid kerogen decomposes
 - Liquid and gaseous decomposition products
 - Carbon char sequestered
- Avoids burning fossil fuels to produce heat for oil
- Low conductivity rock does not require constant heating



**Closed Heat
Transfer Lines**

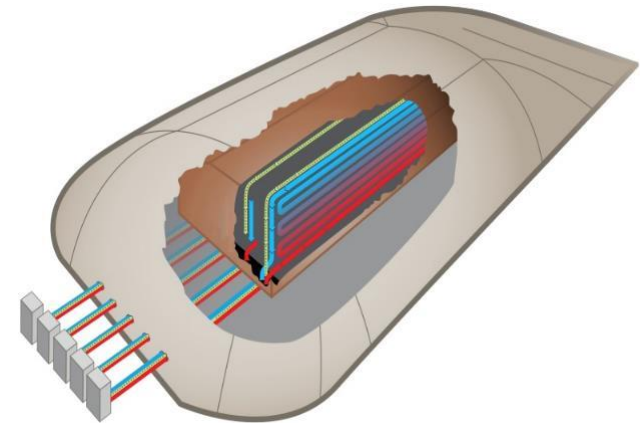
NROSS Limits and Options

● NROSS constraints

- For processes that use indirect heating
- Nuclear reactor temperature limits¹ imply slow heating processes (hundreds of days) that limit required peak temperature of heat input
- Process must be able to have variable heat input

● Many configurations

- Surface or Insitu shale oil conversion
- Heat transfer from reactor to shale oil: steam, propane, other



Surface Retort

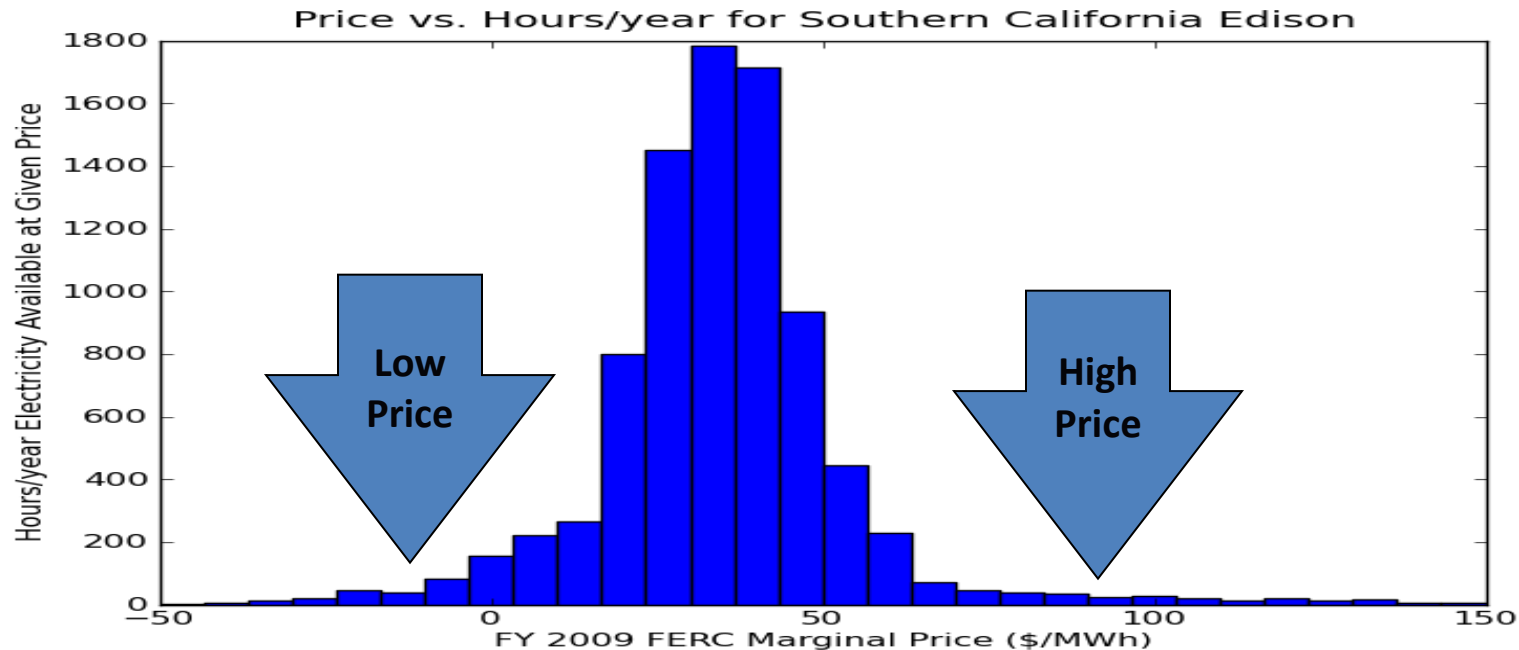
Courtesy of
Red Leaf Resources

Light Water Reactor (LWR) Peak Steam Temperatures Are Insufficient

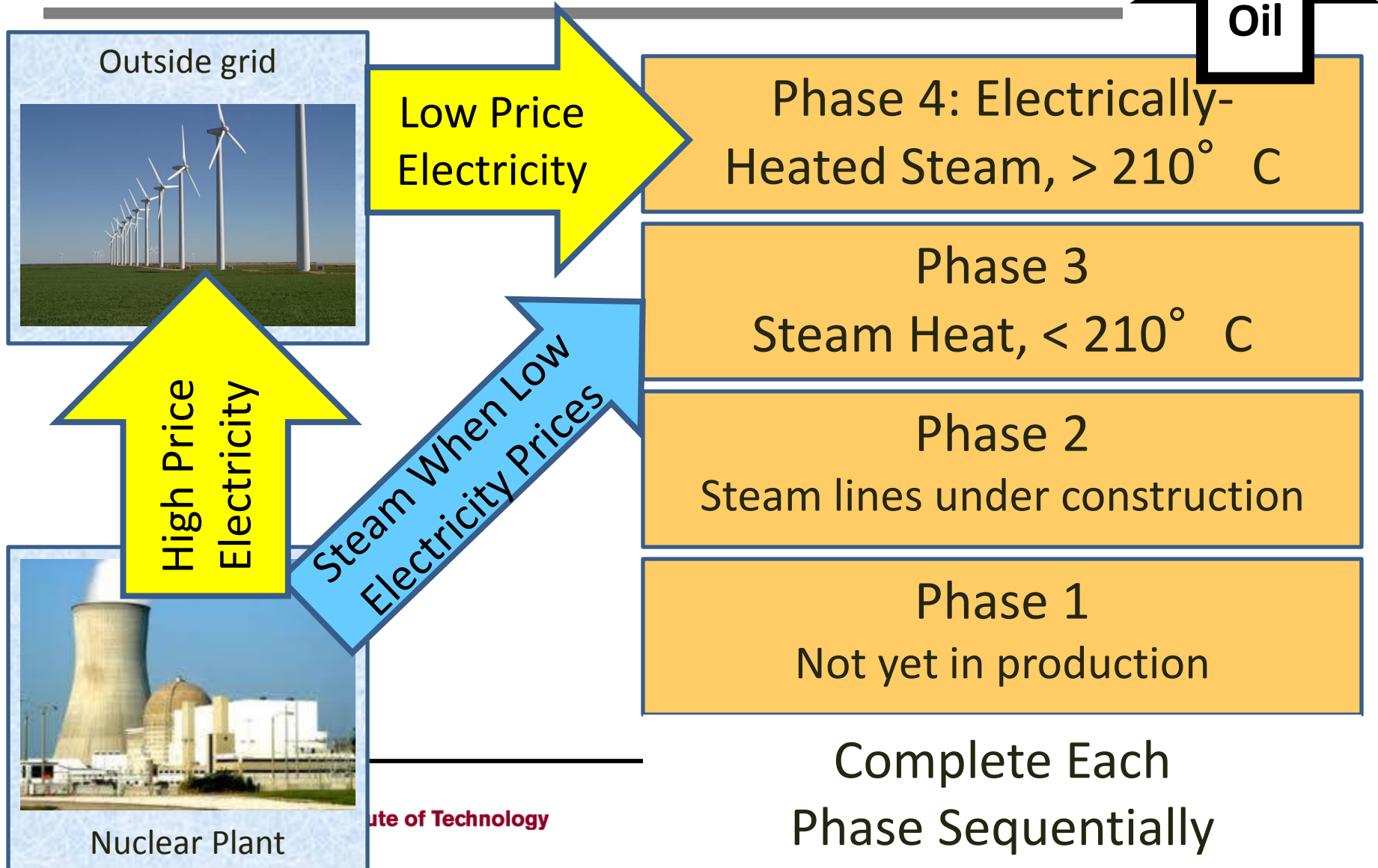
Require Two-Phase Heating of Shale to ~370 C

- Phase 1: Heat oil shale to 210 C with steam heat
- Phase 2: Buy electricity to heat steam to peak temperatures when the price of electricity is low

Electricity Price Distribution



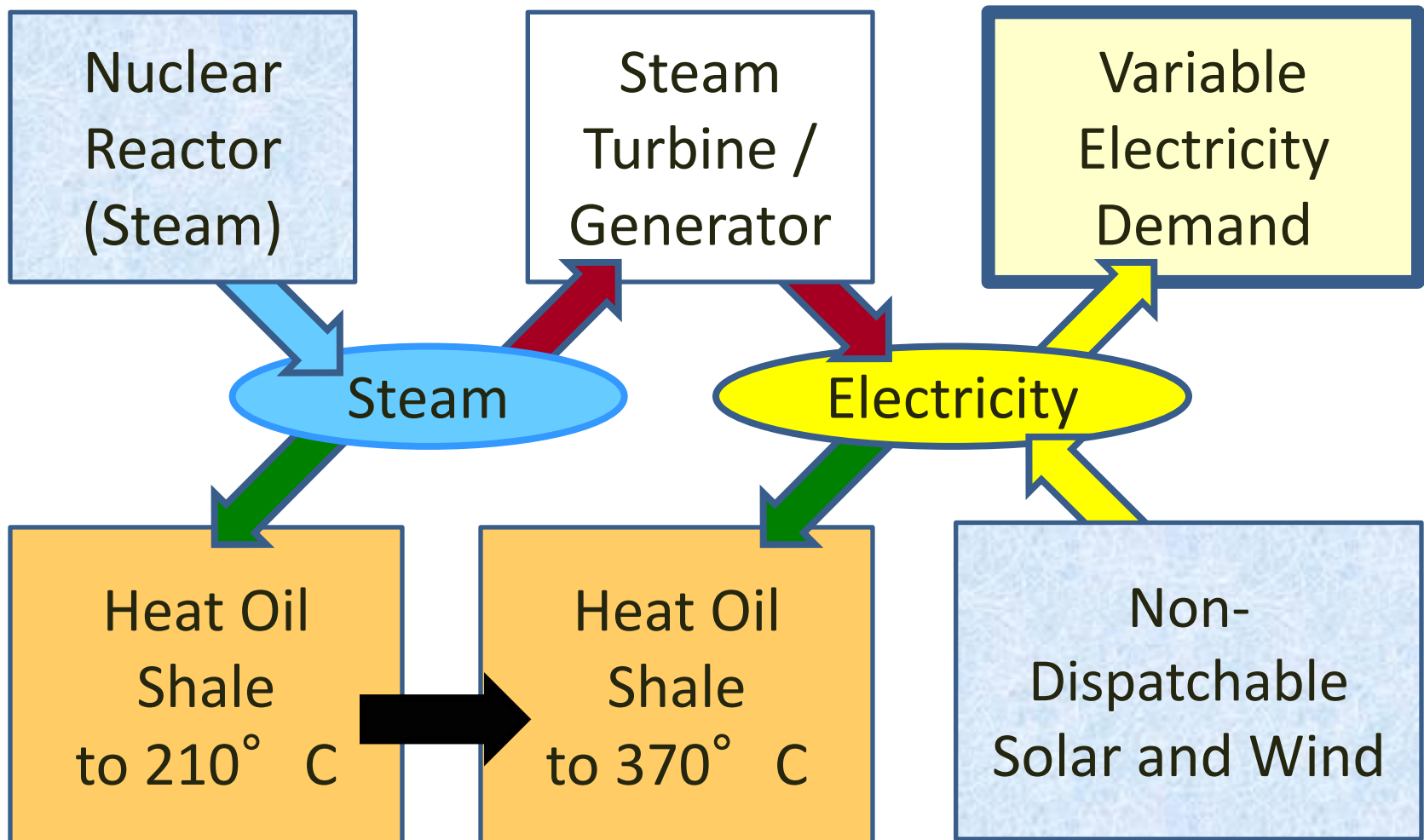
Each Shale-Oil Zone Goes Through ¹⁰ Four Sequential Phases



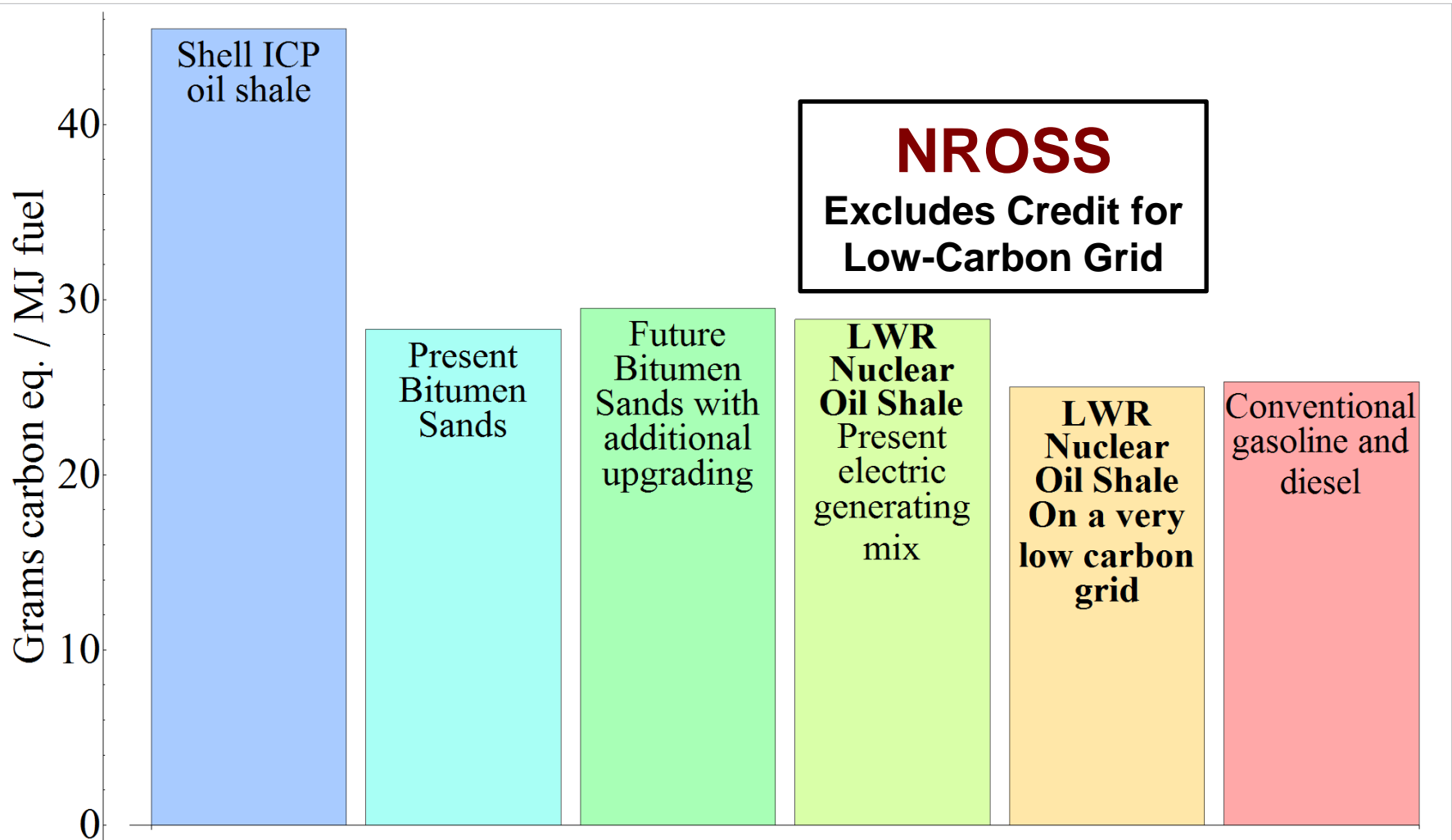
NROSS with LWRs

High Electricity Prices: Electricity to Grid:

Low Energy Prices: Energy to Shale Oil Production



Greenhouse Footprints for Liquid Fuels Production



Production and Combustion of Fuels, Various Production Methods

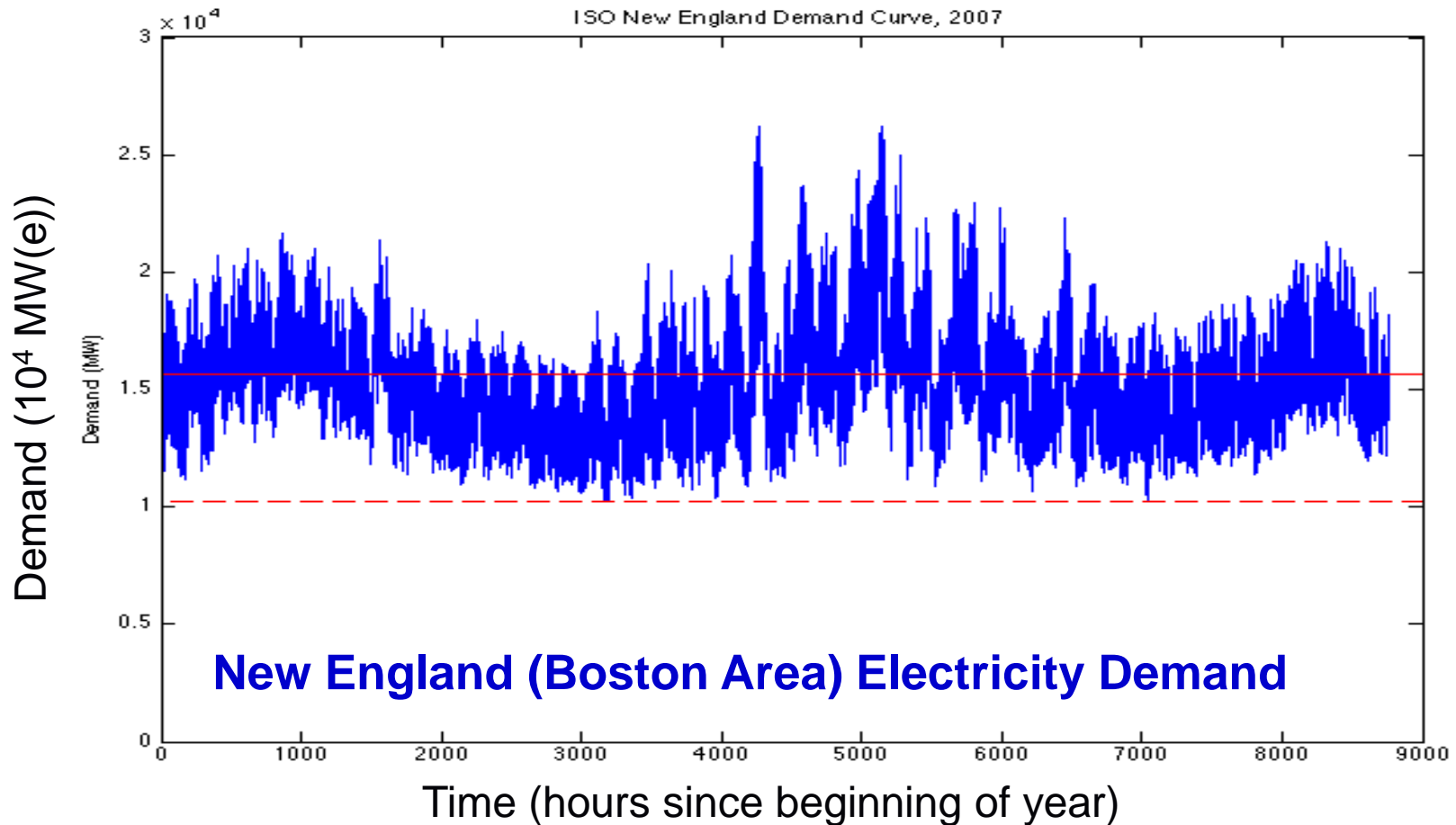
NROSS is a Two Part Story

Oil Shale (Kerogen)

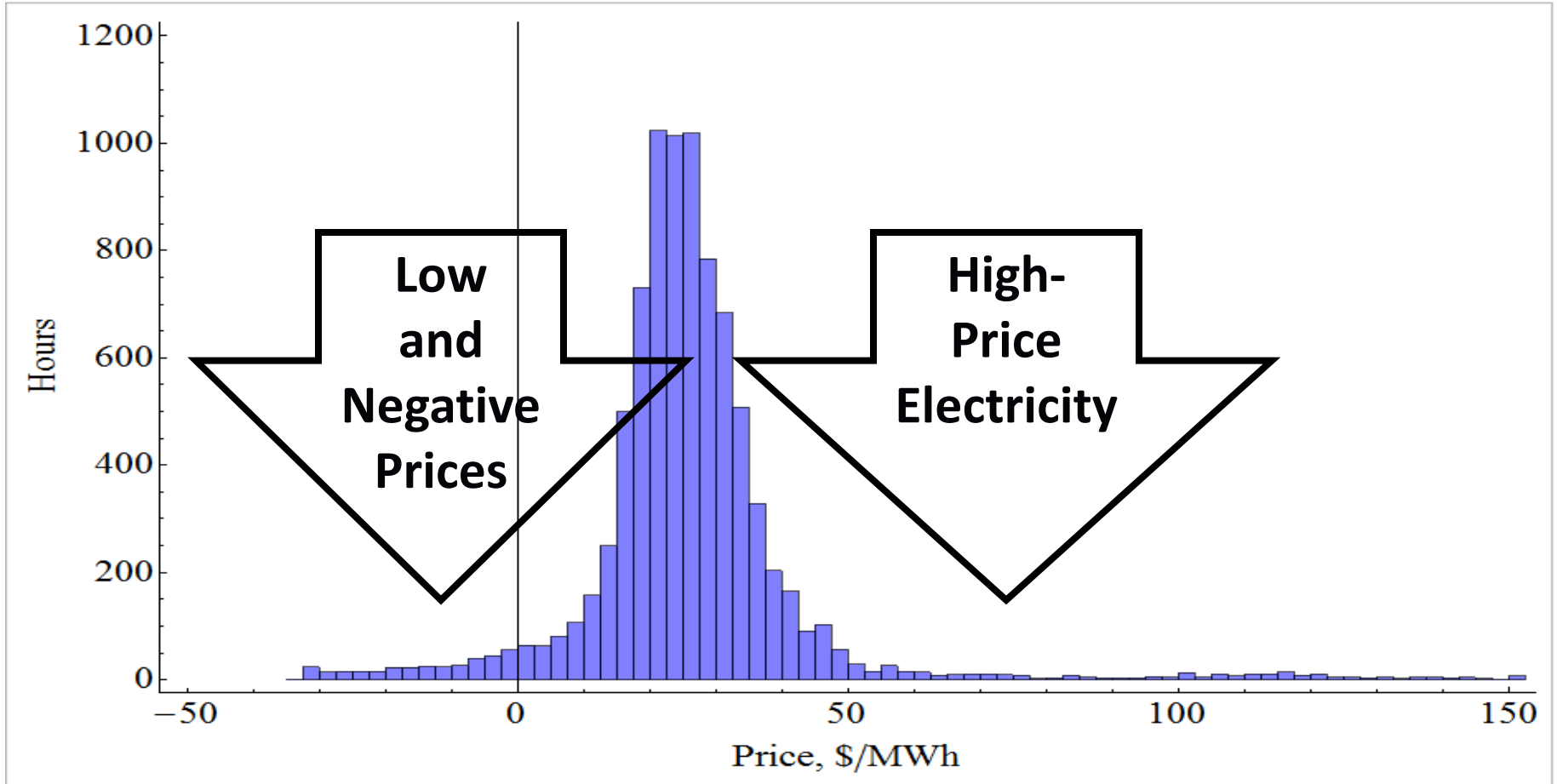
Zero-Carbon Electric Grid

Electricity Demand Varies With Time¹⁴

No Combination of Nuclear and Renewables
Matches Electricity Demand



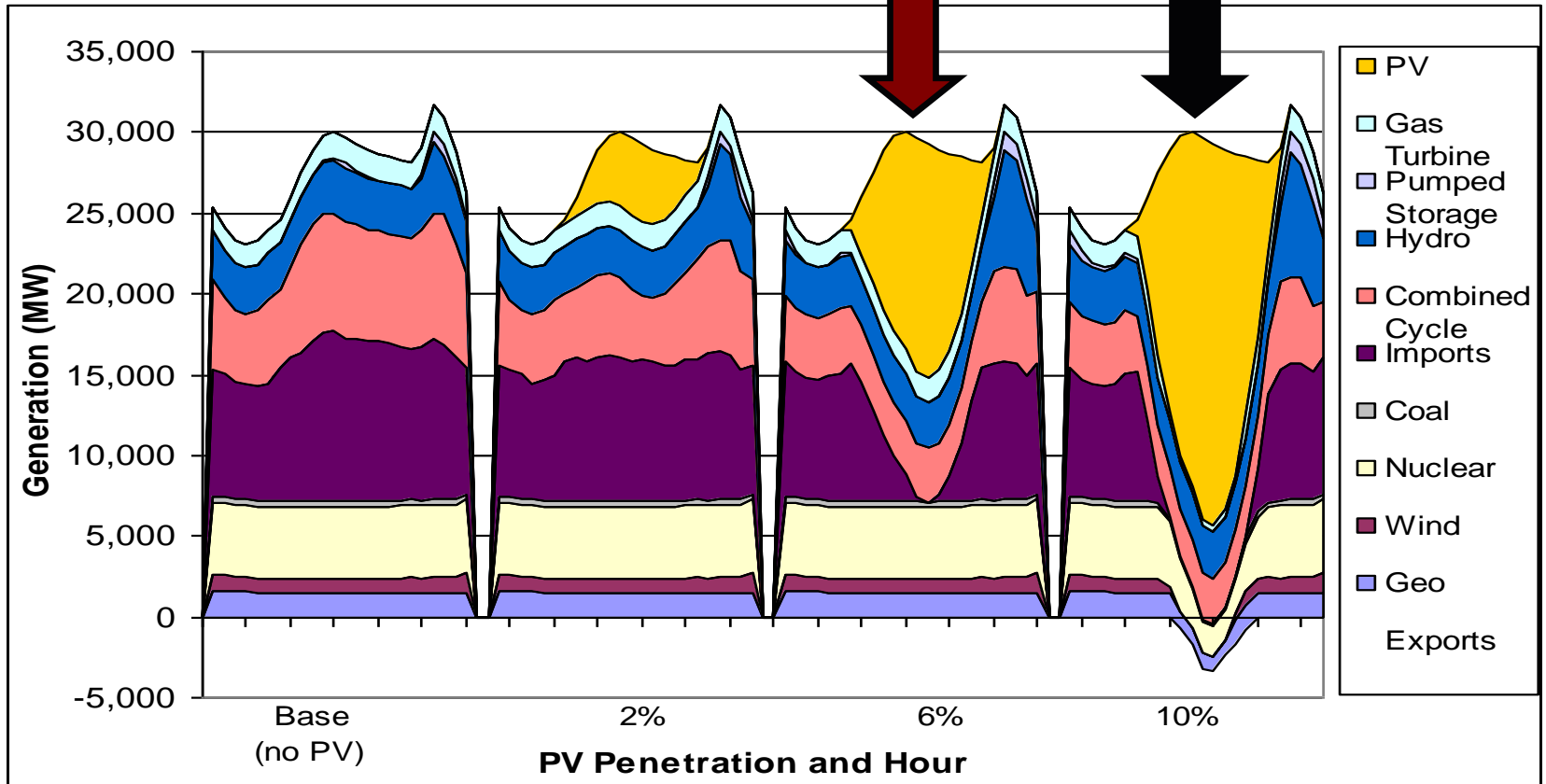
In a Free Market Electricity Prices Vary



Adding Solar and Wind Changes Electricity Prices & Price Structure

Unstable Electrical Grid

Excess Electricity with Price Collapse



California Daily Spring Electricity Demand and Production with Different Levels of Annual Photovoltaic Electricity Generation

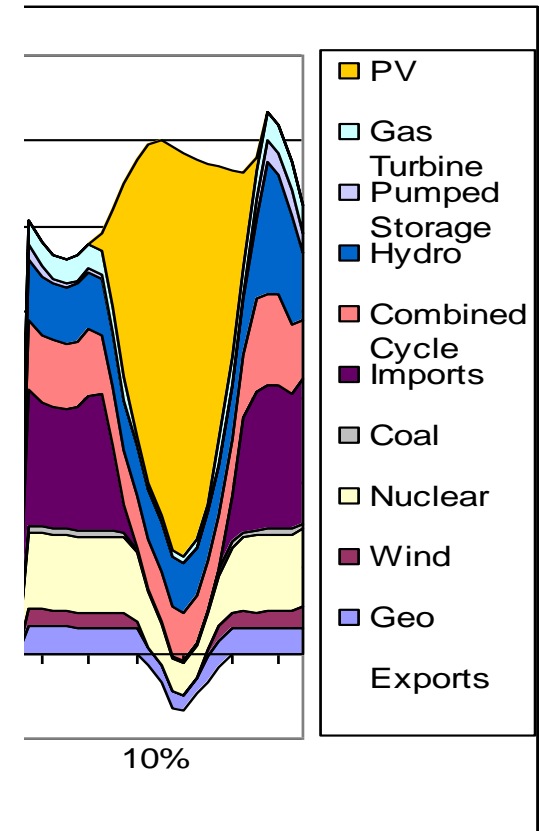
Notes on California Solar Production

17

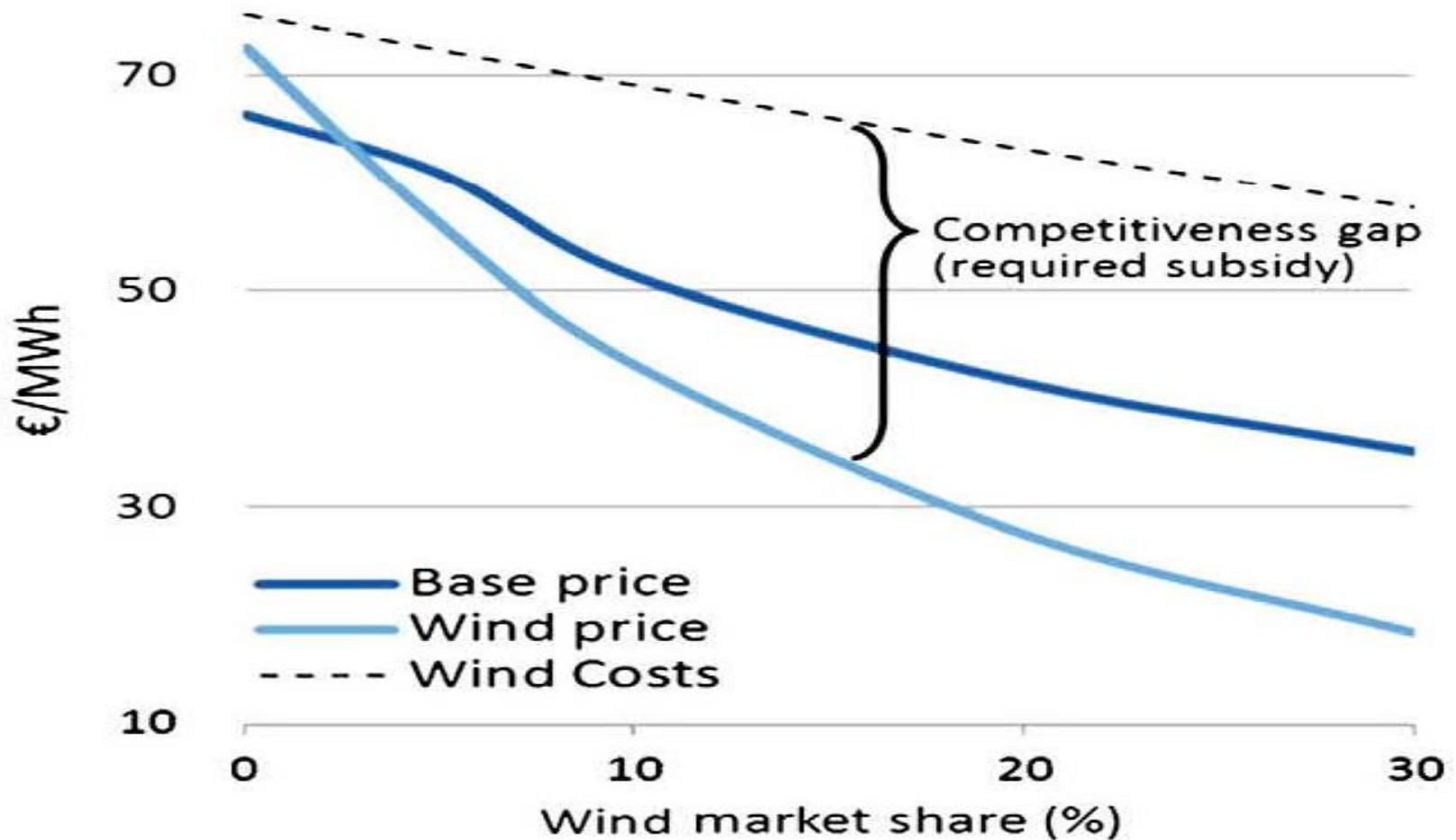
- Far left figure shows mix of electricity generating units supplying power on a spring day in California. The figures to the right shows the impact on grid of adding PV capacity assuming it is dispatched first—low operating cost.
- Percent PV for each case is the average yearly fraction of the electricity provided by PV. The % of power from PV is much higher in late June in the middle of the day and is zero at night. Initially PV helps the grid because PV input roughly matches peak load. Problems first show up on spring days as shown herein when significant PV and low electricity load.
- With 6% PV, wild swings in power supply during spring with major problems for the grid. By 10% PV on low-electricity-demand days PV provides most of the power in the middle of many spring days.
- In a free market PV producers with zero production costs will accept any price above zero. As PV grows, revenue to PV begins to collapse in the middle of the day as electricity prices collapse. Collapsing revenue limits PV new build. Large-scale PV also hurts the base-load electricity market while increasing market for peak power when no sun. In the U.S. that variable demand is getting filled with gas turbines. Similar effects at other times with large wind input. This is one of the reasons why in some cases one has increased greenhouse gas emissions with increased use of renewables.
- The revenue problem with renewables is similar to selling tomatoes in August when all the home-grown tomatoes turn red and the price collapses to near zero
- The other part of the story is the need for backup power when low wind or solar. For example, in Texas only 8% of the wind capacity can be assigned as dispatchable. That implies in Texas for every 1000 MW of wind, need 920 MW of backup capacity for when the wind does not blow—almost a full backup of wind. In the Midwest grid, only 13.3% of the wind capacity can be assigned as dispatchable. Consequently, with today's technologies large scale renewables implies large-scale fossil fuel useage

In a Free Market, Revenue Collapse for Solar at ~10% Total Yearly Electricity

- Each PV owner sells whenever electricity prices above zero
- When PV approaches total demand in the middle of the day, price to near zero
- Less total revenue for each solar addition as more days with low revenue
- The economic barrier for solar



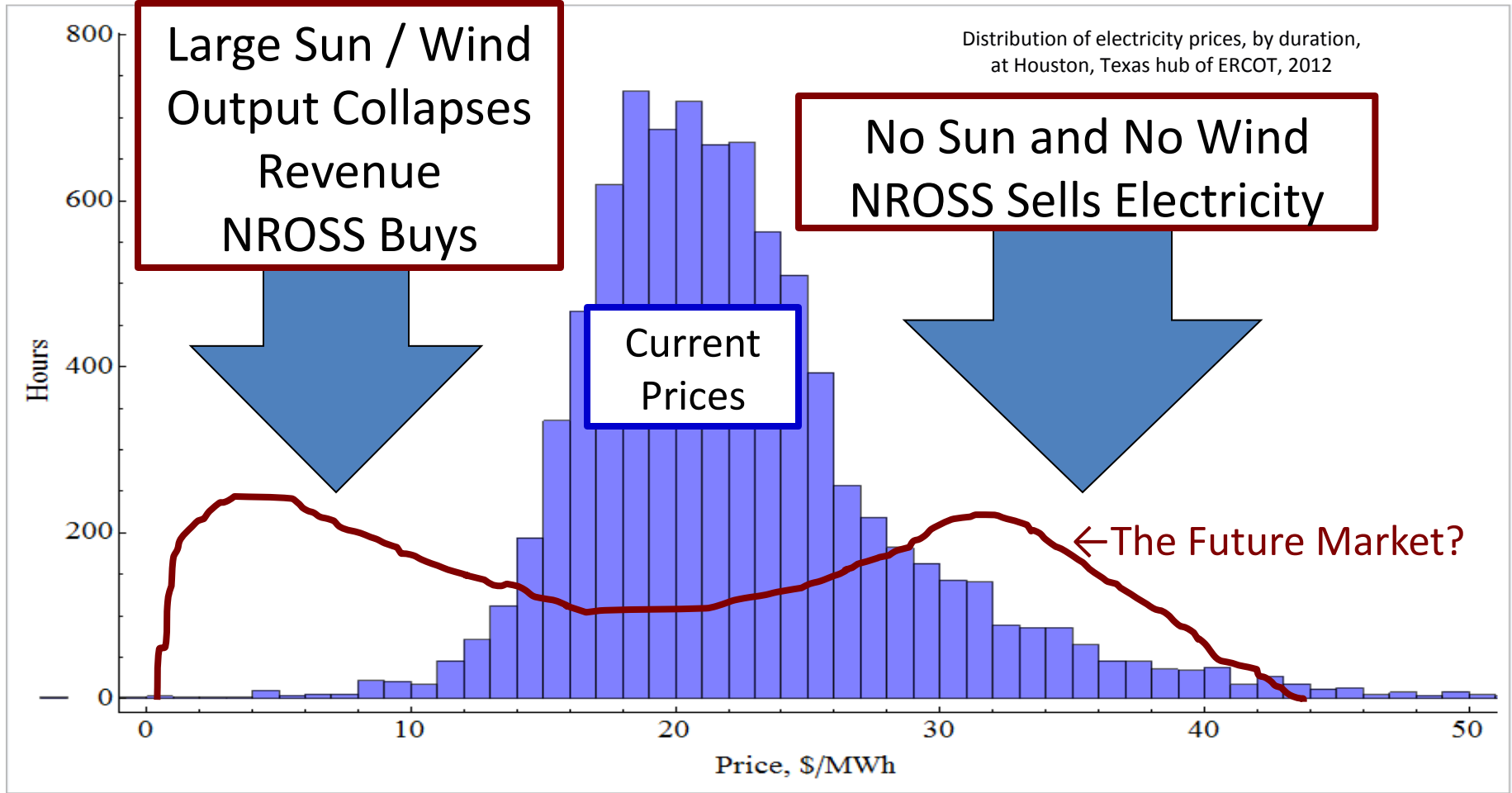
European Electricity Prices Vs. Wind



**Wind Revenue Decreases As Wind Market Share Increases
Because Collapse Prices When High Wind Conditions**



Low-Carbon Electricity Free Market Implies More Hours of Low / High Price Electricity



NROSS Economics Helped by Price Curve

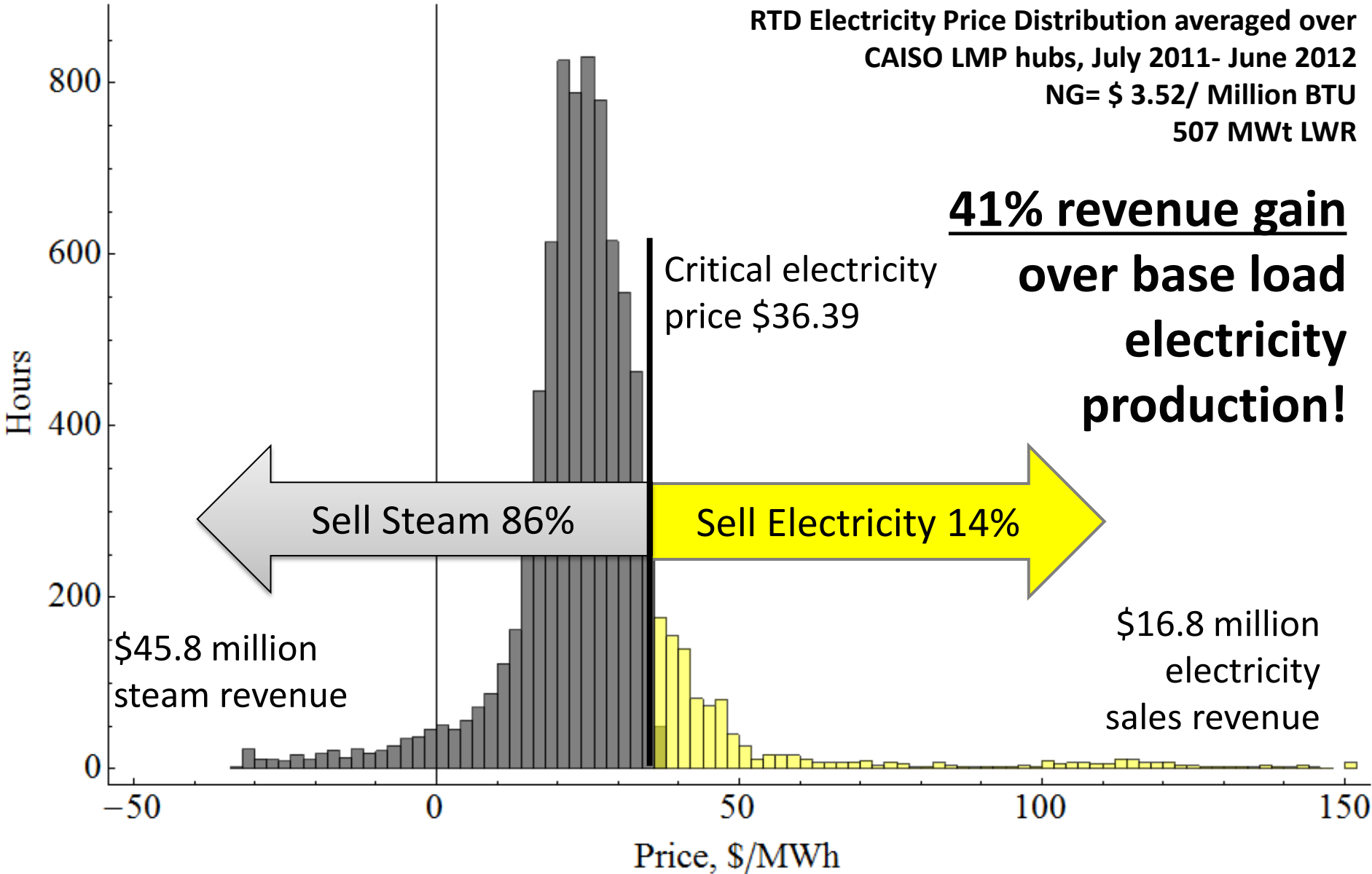
NROSS Enables Zero-Carbon Grid

- Reduces large revenue collapse for renewables that enables larger-scale use of renewables
- Provides non-fossil nuclear electricity when low wind or solar conditions—eliminating expensive fossil fuel backup to renewables
- Full utilization of low-operating-cost high-capital-cost nuclear and renewable electricity generators
- Maximizes NROSS revenue: buy electricity when low prices and sell electricity when high prices

Revenue Assessment Results

RTD Electricity Price Distribution averaged over
CAISO LMP hubs, July 2011- June 2012
NG= \$ 3.52/ Million BTU
507 MWt LWR

41% revenue gain
over base load
electricity
production!



Who Gets Credit for Zero-Carbon Grid?

- NROSS enables economic zero-carbon grid
- Without NROSS zero-carbon grid expensive
 - Low capacity factors for wind, solar, and nuclear
 - Expensive energy storage systems
- **If NROSS oil gets the credit for zero-carbon grid, CO₂ emissions assigned to liquid fuels is less than from combustion of liquid fuels**

Potential For Low-Cost Nuclear Energy Relative Traditional Systems

24

- Shale deposits in small geographic area (10s of miles) but could use 10s of reactors
- Enable serial production
- Enable common facilities
- Enable efficient operations



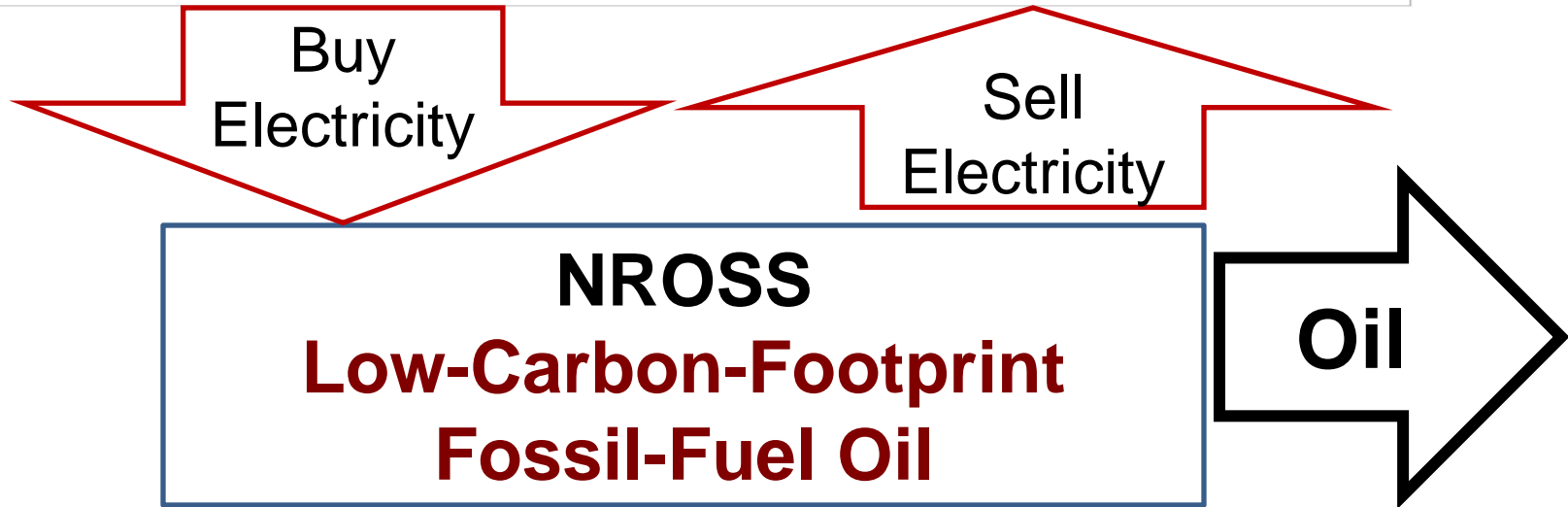
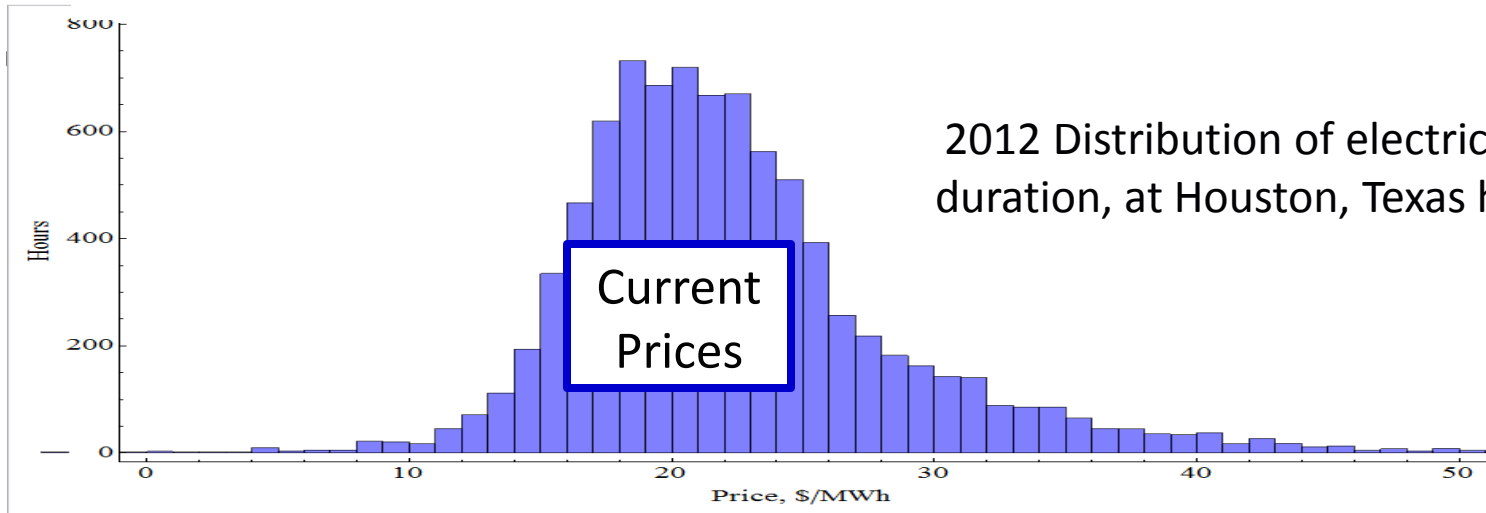
Unique Nuclear Economics of Scale



NROSS Conclusions

- Economic benefits for nuclear, renewable (wind and solar), and oil shale operators
 - Enables renewable expansion by supplying electricity when low wind/low solar and absorbing excess electricity when high wind/high solar
 - **Potentially the least-carbon-intensive fossil source of liquid fuels—makes oil shale (kerogen) the green fossil fuel**
 - Significant development work required
-

Questions?



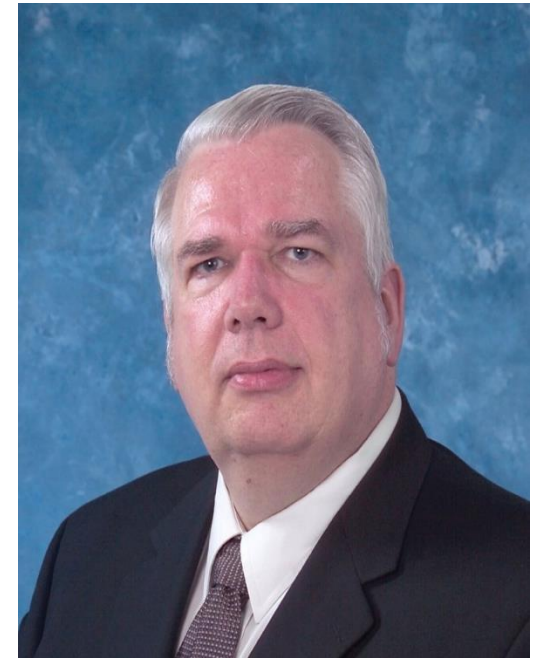
We would Like to Thank Idaho National Laboratory for their Support

Supplemental Information



Biography: Charles Forsberg

Dr. Charles Forsberg is the Director and principle investigator of the High-Temperature Salt-Cooled Reactor Project and University Lead for the Idaho National Laboratory Institute for Nuclear Energy and Science (INEST) Nuclear Hybrid Energy Systems program. He was the Executive Director of the Massachusetts Institute of Technology Nuclear Fuel Cycle Study. Before joining MIT, he was a Corporate Fellow at Oak Ridge National Laboratory. He is a Fellow of the American Nuclear Society, a Fellow of the American Association for the Advancement of Science, and recipient of the 2005 Robert E. Wilson Award from the American Institute of Chemical Engineers for outstanding chemical engineering contributions to nuclear energy, including his work in hydrogen production and nuclear-renewable energy futures. He received the American Nuclear Society special award for innovative nuclear reactor design on salt-cooled reactors and will be receiving the ANS 2014 Seaborg Award. Dr. Forsberg earned his bachelor's degree in chemical engineering from the University of Minnesota and his doctorate in Nuclear Engineering from MIT. He has been awarded 11 patents and has published over 200 papers.



<http://web.mit.edu/nse/people/research/forsberg.html>



NROSS Summary

MAKING OIL SHALE THE FOSSIL FUEL WITH THE LOWEST GREENHOUSE IMPACT PER LITER OF DIESEL OR GASOLINE WHILE IMPROVING ECONOMICS

34th Oil Shale Symposium
Boulder, Colorado; October 13-17, 2014

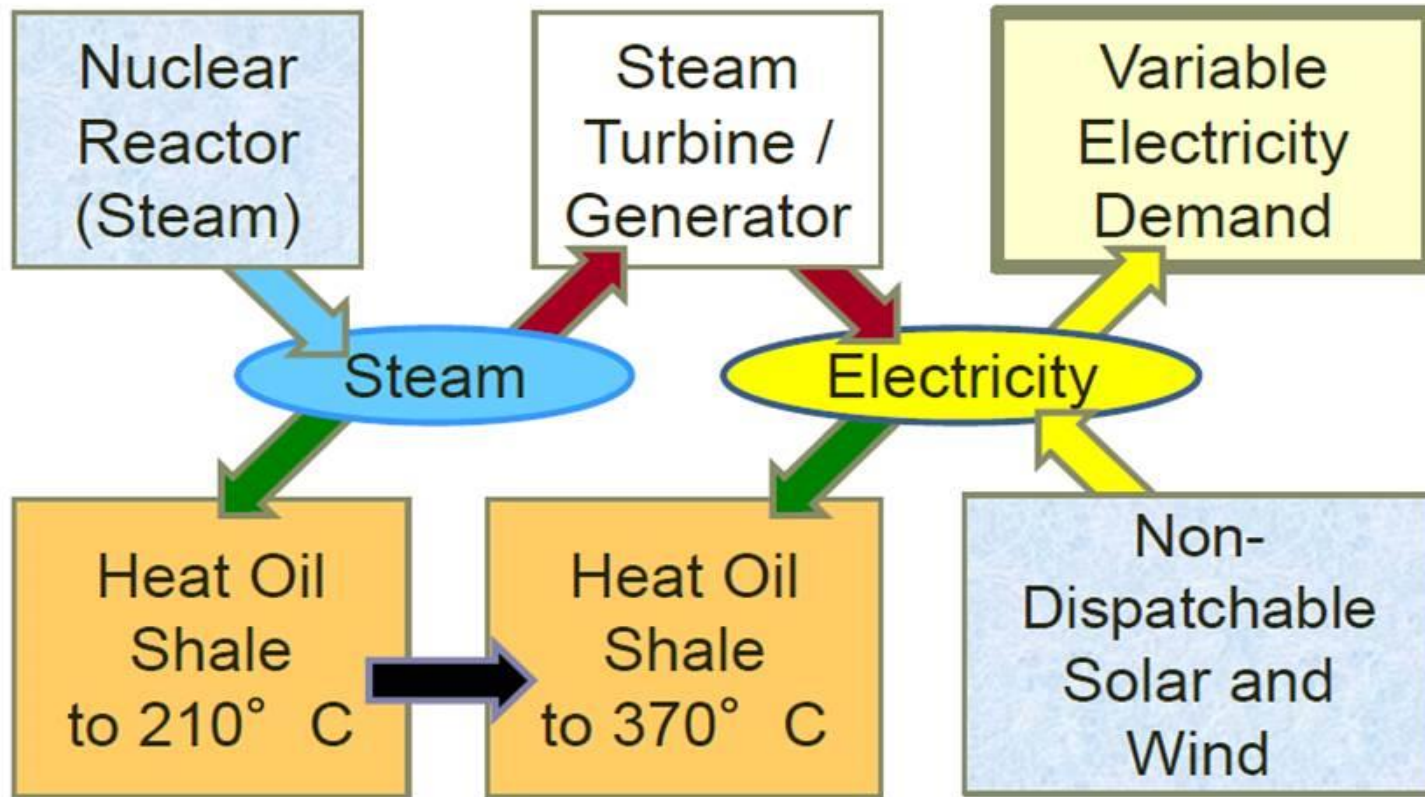
Charles Forsberg and Daniel Curtis
Massachusetts Institute of Technology
77 Massachusetts Ave., Room 24-207A, Cambridge, MA 02139
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Summary – A nuclear renewable shale oil system (NROSS) is proposed with three goals: (1) lowest greenhouse gas emissions of any fossil fuel per liter of diesel or gasoline, (2) enabling technology for a zero-carbon electric grid for the western United States and other areas (eastern Baltic) with large oil shale (kerogen) reserves, and (3) competitive economics. Restrictions on greenhouse gas emissions are increasing in the United States and Europe in the form of carbon taxes and cap-and-trade systems. New restrictions on greenhouse gas emissions from power plants are being implemented. Restrictions will likely be applied to methods to produce liquid fuels. Current methods to produce shale oil have a large greenhouse footprint because of the large quantities of heat required to convert kerogen to liquid fuels in-situ and/or the combustion of char in surface retorts. Oil shale viability may require lowering this greenhouse footprint while improving economics.

The proposed strategy (Fig. 1) for low-carbon shale oil production is to build light water reactors (LWRs) on top of shale oil deposits in Colorado, Utah, and Wyoming. Oil shale heating is accomplished in a two-step process via closed steam lines. Initial heating to temperatures between 220 to 270°C is accomplished using steam from LWRs that have peak steam temperatures near 300°C. In the second stage of heating, electrically-heated steam is circulated to raise shale temperatures to ~370°C for oil production. The LWRs operate at full power with steam being used to heat blocks of shale when the price of electricity is low and producing electricity for the grid when the price of electricity is high. At times of low electricity prices, electricity is purchased from the grid for the second stage of oil shale heating. This strategy minimizes costs of providing steam and electricity for shale oil recovery. The strategy minimizes greenhouse gas emissions per liter of gasoline or diesel .

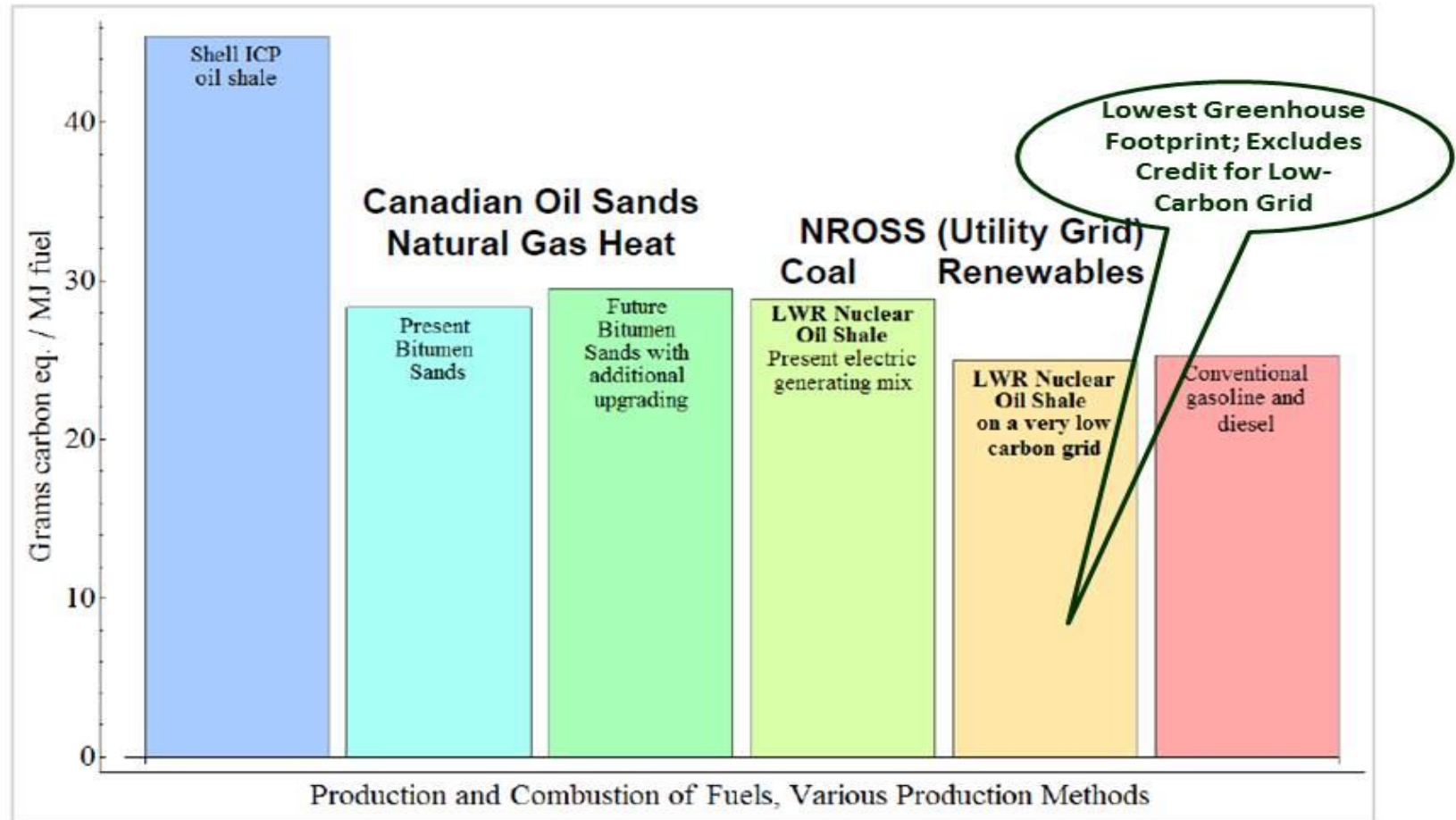
Fig. 1. NROSS System Design



- *Reduce greenhouse gas emissions from shale oil production using heat from nuclear reactors.* Figure 2 shows the greenhouse footprint for different methods of producing fossil liquid fuels from conventional processes, Canadian oil sands, and oil shale. Two different NROSS options are shown. The NROSS-coal option involves buying electricity from the existing Colorado electrical grid that generates a significant quantity of its electricity from coal. The NROSS-renewables option refers to buying electricity from a future Colorado grid where renewables and NROSS replace fossil fuels.
- *Zero-carbon western electricity grid.* NROSS enables a zero-carbon nuclear renewable electricity grid by replacing the use of fossil fuels to provide variable electricity to the grid to match electricity production with demand. The nuclear reactors associated with NROSS provide electricity to the grid at times of low wind and solar conditions. NROSS solves the central problem of renewables—inability to produce electricity on demand. By accident some of the best wind conditions exist close to U.S. oil shale resources—wind that could be economic without subsidies if economic backup electricity can be provided for times of low wind. In the context of NROSS, the question is who gets credit for enabling very-low greenhouse gas emissions from the electricity grid? If NROSS gets credit, the greenhouse footprint from such shale oil would be less than the greenhouse gas emissions from burning the gasoline and diesel. This is not accounted for in Figure 2. This NROSS feature implies a lower greenhouse footprint than shale oil produced with renewable energy inputs or options with carbon dioxide sequestration. NROSS becomes the option with the lowest greenhouse releases of any method to produce liquid fuels from fossil fuels.

Fig. 2. Greenhouse Footprints for Liquid Fuels Production

U.S. Case: Shale Oil in Colorado



•*Minimum production impact.* U.S. oil shales are the most concentrated fossil deposits on earth. It is more economic and more efficient to control emissions over a small area per liter of fuel than over a large area. This avoids situations such as in North Dakota where a quarter of the natural gas being produced as a co-product of oil production is being flared. The implications for real world operations is the potential for significantly lower total environmental impact per liter of fuel—although there will be significant local impact.

NROSS is potentially viable where there are large rich oil shale deposits, lower-cost renewables, and large demands for electricity. This includes the western United States and potentially the Eastern Baltic region (Estonia, Russia, Sweden). From a global perspective if the goal is to minimize greenhouse gas releases to the atmosphere, NROSS may be the preferred global source of liquid fossil fuels. NROSS is built upon three system characteristics: (1) nuclear power has a very low carbon footprint, (2) the extraordinary oil shale deposits that allow a nuclear plant to produce steam for its lifetime with limited lengths of steam lines and (3) the slow heating process for oil shale that does not require steady-state heat addition and thus enables the nuclear power plant to operate economically at full power while providing variable electricity to the grid and variable heat for shale oil production. If for any reason it was decided not to continue shale oil production, the nuclear facilities would remain in operation for electricity production.



Nuclear plant costs for shale oil production would be expected to be significantly lower than for traditional nuclear power plants. Depending upon reactor size, tens to hundreds of reactors would ultimately be built—a totally unique set of conditions for nuclear plant construction. This enables serial manufacturing and the economics of manufacturing. The small geographical area allows prefabrication of very large plant modules in a central shop with transport to local construction sites to minimize cost, improve quality, accelerate construction, and avoid weather delays. The small geographical area allows common services for many reactors from administration to security to spent nuclear fuel storage. There is the option to use initial heating of the shale blocks as the heat sink for the power cycle—avoiding air or water cooling.

There are major technical and institutional challenges to be addressed before such a strategy can be implemented. Added development work is required for heating of oil shale using steam in enclosed lines. The institutional challenges may be larger and include dealing with multiple regulatory agencies, the historical belief system that oil shale is one of the dirtiest sources of liquid fuels, the business model for coupling the electric sector with the liquid fuels sector, and who gets credit for reduced greenhouse gas emissions by the electricity grid. NROSS creates a shale oil option that minimizes greenhouse gas emissions, supports national policies to reduce those emissions and is a domestic source of liquid fuels. Because most oil shale is on Federal lands, building the case that oil shale can be part of the solution to a low-carbon, domestic liquid fuel source is required for any path forward.

Acknowledgement

We would like to thank Idaho National Laboratory for their support of this work



Zero-Carbon Hydrocarbon Fuels

The Grand Challenge for a World with No Net Releases of Carbon Dioxide to the Atmosphere

Fossil Liquid Fuels with CO₂ Sequestration

Biofuels

Fuels from Air and Water

Option 1: Use Fossil Fuels; Remove and Sequester CO₂ from Air

- Burn fossil liquid fuels
- Remove CO₂ from air and sequester CO₂
 - Work underway to capture CO₂ from air
 - Energy costs appear to be fraction of energy value from burning the fuel
 - Locate carbon-dioxide removal from air anywhere on earth: sites chosen for the lowest total costs
- Energy inputs may be lower than other zero-carbon hydrocarbon fuel futures—depending upon energy requirements for carbon capture

Creates Large Incentives to Minimize CO₂ Releases from Fossil Liquid Fuels Production—such as Using NROSS

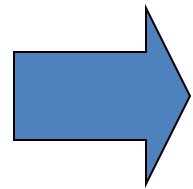
Option 2: Biofuels—But Is There Enough Biomass Worldwide?

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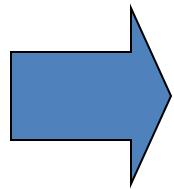
- Plants produce biomass by removing CO_2 from atmosphere so no net CO_2 emissions if convert to liquid fuels and burn
- Production limited by feedstock availability so need efficient use of biomass
- U.S. biomass potential in barrels oil-equivalent / day
 - Energy if burn: ~10 Million barrels per day
 - Liquid fuel if biomass feedstock and used as energy input to biofuels plant: ~ 5 Million barrels per day
 - Liquid fuel if biomass feedstock and external energy and H_2 for biofuels plant: ~12 Million barrels per day
- **Potential for biofuels production depends upon external energy sources and hydrogen**

Option 3: Liquid Fuels from Air or Water: Hydrogen Intensive

Extract CO₂



Convert CO₂ and H₂O To Syngas

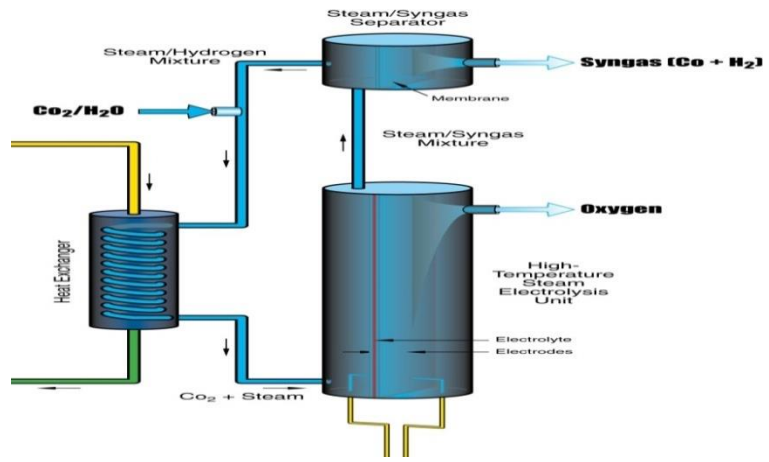


Conversion to Liquid Fuel
CO + H₂ → Liquid Fuels

Heat + Electricity



Carbon Dioxide From Air



High Temperature Electrolysis (One Option)



Fischer-Tropsch Process

Large Energy Input to Convert CO₂ to Liquid Fuels

Renewable Economics

Backup Electricity is the Challenge



Energy Economic Realities

EIA Unsubsidized Power Cost Estimates Next Page

- The competitive electricity sources are natural gas, coal, and nuclear
 - Significant regional differences favor one over the other in specific circumstances
 - Fossil fuel electricity costs are highly sensitive to variable fuel prices and any greenhouse gas constraints
- The potentially competitive renewable today is land-based Mountain and Great Plains wind
 - Only limited good land-based wind resources elsewhere in U.S.
 - Usually non-competitive without subsidy because (1) its non-dispatchable and requires peaking gas turbine to provide electricity when low wind conditions and (2) large-scale use depresses prices when good wind conditions
 - Is potentially competitive if hydro, NROSS, or similar system to (1) provide year-round low-cost backup electricity and (2) absorb electricity when high wind conditions to avoid revenue collapse

EIA Cost Estimates for 2018 (\$/MWh)

From: Levelized Cost of New Generation Resources in the Annual Energy Outlook 2013: January 2013

Plant type (Capacity factor)	Levelized Capital (Includes Transmission Upgrade)	Fixed/Variable O&M	Total
Dispatchable			
Coal (85%)	66.9	4.1/29.2	100.1
Coal with CCS (85%)	89.6	8.8/37.2	135.5
NG Combined Cycle (87%)	17.0	1.7/48.4	67.1
NG Turbine (30%)	47.6	2.7/80.0	130.3
Nuclear (90%)	84.5	11.6/12.3	108.4
Non Dispatchable			
Wind (34%)	73.5	13.1/0.0	86.6
Wind offshore (37%)	199.1	22.4/0.0	221.5
Solar PV (25%)	134.4	9.9/0.0	144.3
Solar thermal (20%)	220.1	41.4/0.0	261.5

High Operating Cost Fossil

High Capital Cost Non-Fossil

All Except Natural Gas Turbine Assumed to Operate at Maximum Capacity: Very Expensive If Part Load

- Solar high cost is a consequence of low capacity factors (night-day summer-winter variations in sun light); thus, the cost per kilowatt can be lower than many other generating sources but there is no output at night. Large (factor of 2) variations depending upon location. Requires gas turbine backup for times of low solar output
- Economic wind is almost all on the Great Plains from Texas to the Dakotas. Costs rise dramatically as wind speeds decrease. Offshore wind expensive because costs of foundations and cost of operations at sea. Requires gas-turbine backup for times of low wind output
- All assumed to operate at maximum capacity except for the natural gas turbine with its 30% capacity factor. In the U.S. gas turbines are the preferred method to meet variable electricity demand. Old coal plants are also used for variable electricity production. In countries such as France, nuclear plants have operated with variable output for decades.

Added Information



Further Reading

- D. Curtis, and C. Forsberg, “Light Water Reactor Arrays for Production of Shale Oil and Variable Electricity,” presented at the ANS Annual Meeting, June 16-20, 2013, Atlanta, Georgia, USA
- D. Curtis and C. Forsberg, “Nuclear Heat And Power For In-Situ Shale Oil Production And Variable Electricity,” presented at the 33rd Oil Shale Symposium, October 14-16, 2013, Golden, Colorado
- D. Curtis and C. Forsberg, “Nuclear Oil Shale—Partnership Opportunity for Expanded Domestic SMR Market,” American Nuclear Society Winter Meeting, Washington D.C., November 10-14, 2013
- D. Curtis, C. Forsberg, M. McKellar, and E. Mattson, “A Demonstration Project Coupling a Small Modular Reactor with a Hybrid Nuclear Renewable Oil Shale System”, presented at ICAPP 2014, Charlotte, April 6-9, 2014.

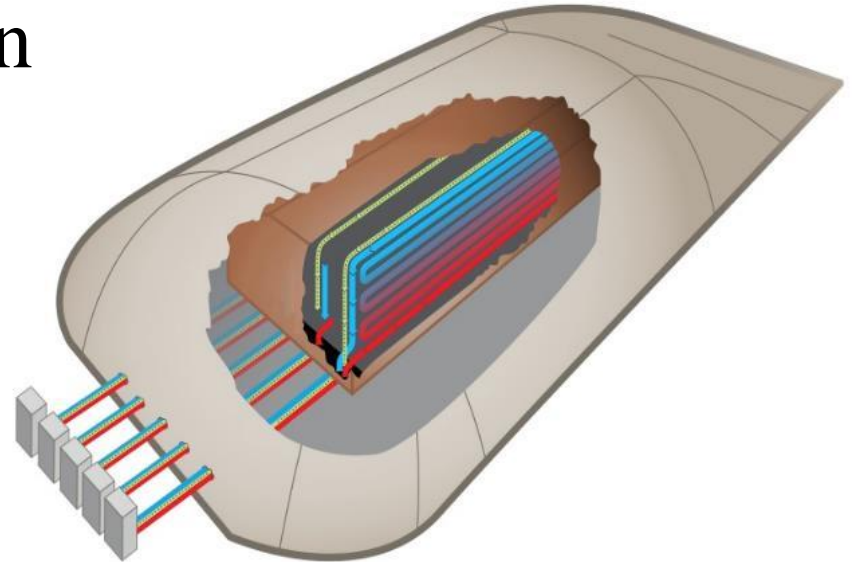
Natural-Gas Fracking Technology is Improving Insitu NROSS Economics

- Shale gas fracking has developed “factory” drilling with major reductions in drilling costs and performance improvements
 - Economics of scale by drilling multiple wells in a small geographical area
 - Lower-cost drilling rigs customized for drilling in a specific geology
 - Accurate horizontal drilling for long distances by using drilling information on first wells to inform drilling on nearby wells
- NROSS drilling for insitu processes is similar to that found in the natural-gas fracking industry

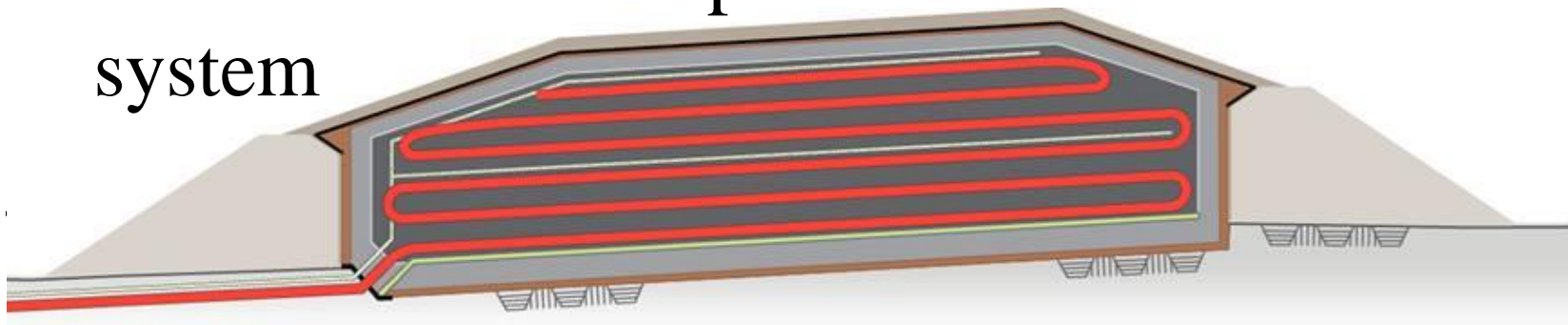
NROSS Applicable to Surface Retorting⁴⁷

Example: Red Leaf Resources Process

- Crushed shale placed in lined cell
- Slow heating with convective gas flow to transfer heat from closed pipes to shale
- Cell is the final disposal system

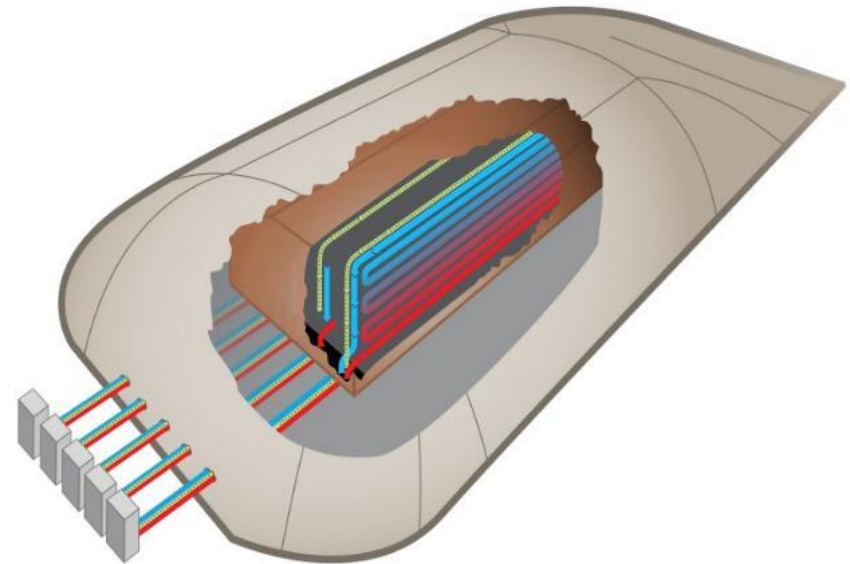


Courtesy of
Red Leaf Resources

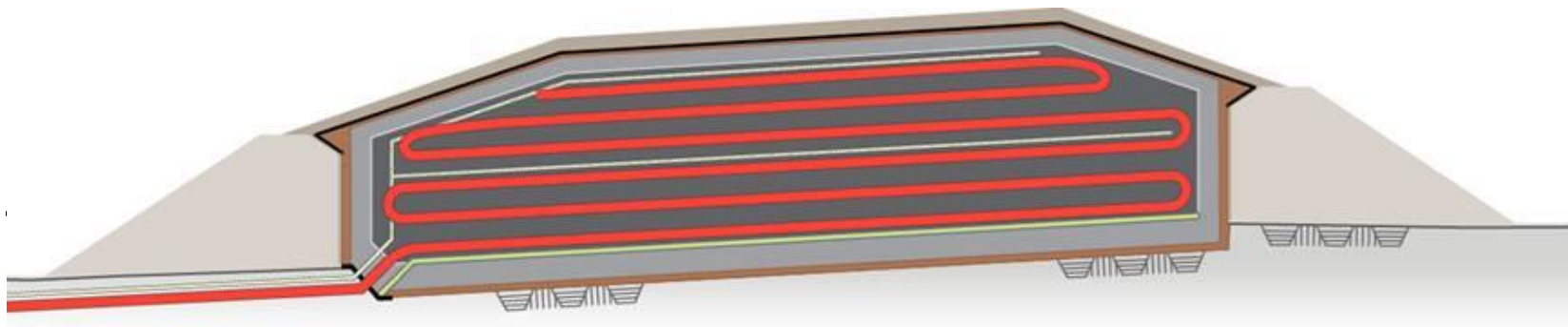


NROSS Can Have Low Water Consumption

- Reactor power system heat sink production is the shale—needs heat
- Implies only high and intermediate pressure steam turbines



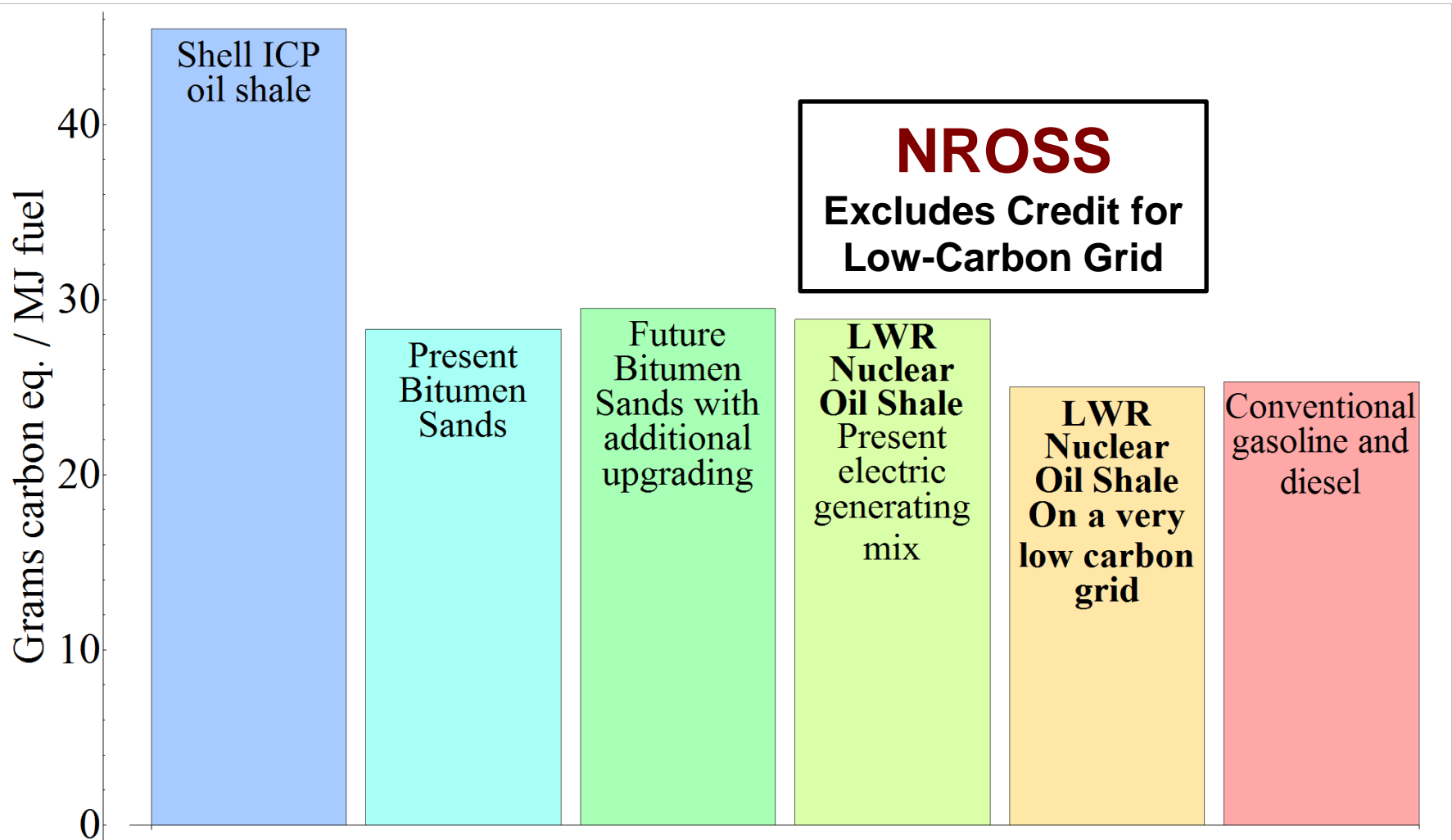
Courtesy of
Red Leaf Resources



Assumptions: Emissions

- Nuclear emissions at 2012 industry average per unit electric output
- Construction and material inputs match Brandt 2008 analysis of Shell In-Situ Conversion Process (ICP)
- Heat input per unit hydrocarbon product matches Shell ICP
- Half of that heat input from nuclear heat
- Half from current Colorado electricity mix
- 59% coal, 23% natural gas, balance zero carbon renewables
- 2011 sector average emissions used for each generator type
- Half of nuclear thermal power in 1 year provides stage 1 heat; half provides electricity

Greenhouse Footprints for Liquid Fuels Production



Production and Combustion of Fuels, Various Production Methods

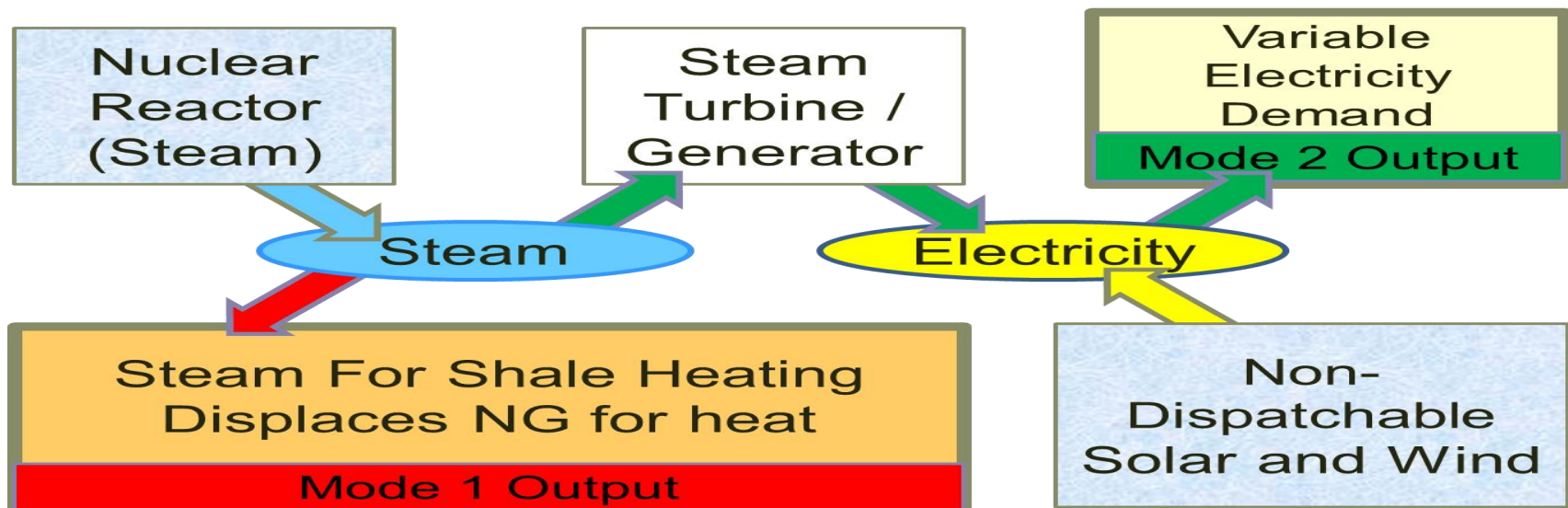
Data Used Greenhouse Footprint Calculations for Liquid Fuels Production

Emissions source (US average data, 2011)	Emissions (g _{ceq} / MJ)	Energy type
Nuclear power plants	4.4	Electricity
Natural gas generators	30.5	Electricity
Coal generators	75.3	Electricity
Colorado grid	51.8	Electricity
Shell ICP	45.45	Fuel
Present bitumen sands	28.3	Fuel
Future bitumen sands	29.5	Fuel
LWR Nuclear Oil Shale	28.9	Fuel
Very-low-carbon grid	25.0	Fuel
LWR Nuclear Oil Shale		
Conventional production of gasoline	25.3	Fuel

Argonne is the source for the oil sands data; Adam Brandt at UC Berkeley for Shell ICP; and EIA for the rest. The top half includes factors used in calculations; the bottom half shows the values represented on the bar chart

Revenue assessment

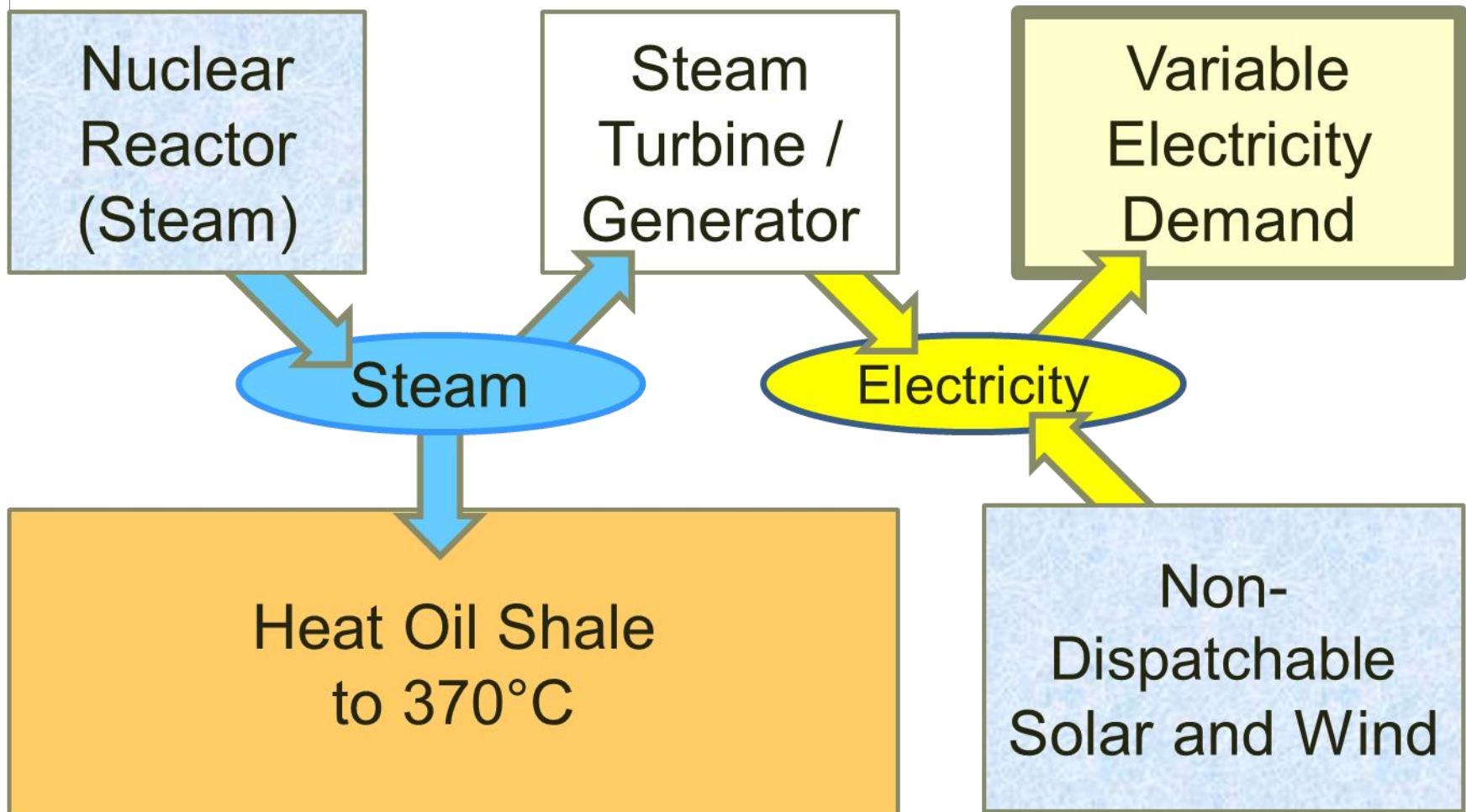
- Two operating modes: steam to shale heating; or electricity to the grid
- System parameters lead to market-independent critical electricity price
- Use hourly electricity market data to determine time in each mode and yearly revenue
- Revenue comparison: oil shale operations vs. baseload power using the same plant



Assumptions: Revenue Analysis

- Mode 1: Sell steam to petrosystem operator, displacing natural gas for preparation heating
 - Steam value set at $0.9 * \text{NG price}$
 - Mode 2: Sell electricity to the grid
 - Check each hour and operate in the favored mode
 - Assume instantaneous change from one mode to the other on the hour when needed
 - The petrosystem operator is buying excess grid electricity for phase 2 heating themselves
 - Switch between modes at a critical electricity price to maximize revenue
-

Nuclear Oil Shale System Option With High-Temperature-Reactors



Fluoride-Salt-Cooled High-Temperature Reactor Oil Shale System Option

