Securing Our Energy Supply with Coal and Small Modular Reactors

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Increasing regulations over carbon dioxide emissions challenge current coal consumers forcing a massive change in existing infrastructure. A utility is forced with the decision of how to balance these changes while minimizing their overall cost of generation. Conventional wisdom states, this can only be done by maintaining existing markets at elevated costs. The purpose of this paper is to show how a utility can manage the risks. can be done while entering new markets and containing any foreseeable regulatory uncertainty.

Combining mature technologies in a novel fashion allows sustainable consumption of fossil fuels, while minimizing overall carbon footprint. This paper will show how a utility can reuse most of its existing infrastructure to decarbonize electricity generation and diversify their revenue base to include transportation and pipeline fuels using next generation nuclear reactors. This approach minimizes stranded asset costs by reusing most existing capital and maintains current coal consumption. Key to the Nuclear Coal-to-Liquid approach is a novel gasifier design that has a cold gas efficiency of 110% and an overall thermodynamic efficiency of the site, including liquefaction of 66.6%.

INTRODUCTION

Implementation of new environmental regulations on already constrained energy supplies poses a significant risk to future economic output. The challenge of creating useful forms of energy on a scale that can affect the global economy while simultaneously providing secure and reliable energy and minimizing environmental impact is the "quest" of our age.[1] Conventional approaches answer this quest with various means but abandon much of our existing capital infrastructure. The purpose of this paper is to lay out an alternative approach to completing the "quest" while preserving the value of existing capital assets.

Coal as a resource is valuable. However, when consumed in its raw form, it creates an environmental burden that is regulated often with significant cost. If coal consumers do not voluntarily alter their consumption patterns, recent and future regulations along with current market forces will make it cost prohibitive to simply burn coal.[2-7] A different approach is needed if coal producers and coal consumers are to preserve the value of their existing capital.

Conventional Coal-to-Liquids (CtL) can reuse our existing infrastructure, however, it significantly reduces the efficiency of electricity generation because of the requirements for carbon dioxide controls under the new and future regulations. The Integrated Gasification Combined Cycle, IGCC, portion of a state-of-the-art dual stage gasifier has the capital costs on par of a new nuclear plant, with nearly three times the cost of the fuel. The high capital and high fuel costs of such dual cycle gasifiers makes them cost prohibitive to build and operate.

Nuclear heat provides a high density and highly reliable and inexpensive heat source of carbon free energy resolving many of the issues of pursuing a conventional CtL strategy. Nuclear heat is inexpensive and can readily provide ample energy to domestically produce the liquid fuels and electricity that our economy relies upon. Nuclear Coal-to-Liquids (NCtL) also provides utilities with the ability to reuse most of existing coal power plants including the coal handling yard, steam plant (when desirable), rail lines, and electricity transmission infrastructure.

The intent of this technological approach is to minimize the amount of new construction where possible and to continue using what already exists in its current role to the greatest extent practical. The first actors would more than likely exist in regulated electrical markets and already have a fleet of nuclear reactors. The regulated utilities would have a higher portion of guaranteed return on equity for the capital investment and would defray some of the risk of volatile transportation and pipeline fuel markets while leveraging their experience in nuclear operations.

With the exception of the reactor and the use of super critical carbon dioxide (S-CO_2) power cycles the design approach was to use technologies that have either been commercially deployed or have undergone full-scale demonstrations. The reactor design chosen is the most mature of fourth generation reactors, General Electric Hitachi's, GE-H, Power Reactor Innovative Small Module, PRISM. This design is ready for a demonstration project.[8] It is based off of a prototype design that operated for over 30-years in Idaho. Other reactor designs are available and NCtL can easily be adapted to suit them. S-CO_2 heat engines offer a compact and efficient technology and represent the lowest Technological Readiness Level, TRL, within the NCtL concept. The S-

CO_2 designs are at engineering scale demonstrations. The demonstrations are nearly the size needed for NCtL and are less of a technology stretch than suggested by their TRL.

This paper will describe a conceptual model that enables NCtL and compare it to existing state of the art conventional CtL. The paper will then propose a methodology for assessing the economics of a NCtL facility.

DESCRIPTION OF THE ACTUAL WORK

Part I: Nuclear Coal-to-Liquids Conceptual Design

The design originated as a way to minimize the impact of potential climate change legislation to coal producers, transporters and end users. The national energy infrastructure is designed for fossil fuels and to forgo their use in a scant 40-years could significantly damage the economy by curtailing energy use through inflating energy prices.

The NCtL implementation strategy is to replace the heat source of existing coal plants, abandoning only the capital invested in the boiler. The reactor would directly repower the existing steam plant. The coal-handling yard would process the current coal quantities from the same suppliers. Thus the producers and shippers may not see any change in existing coal contracts.

The ability of implementing NCtL is not limited to a few particular sites. Repowering a coal plant with a nuclear plant is feasible under current regulations at about 75% of the sites around the country.[9] This is a large market that spans the country. NCtL has a very large market that it can explore and potentially create.

The output of the gasifier and liquefaction are not optimized for a particular product. Instead, the design focused on spanning a breadth of markets: electricity, transportation fuel, and pipeline gas. Spreading the revenue sources over several markets ensures long-term economic viability and insensitivity to volatility in a particular market.

Mine-mouth gasification was considered and dismissed for three reasons: it does not reuse existing capital, it uses almost as much water as it does coal 1.5:1 by mass, and it requires the construction of new distribution networks for all products produced.

The distribution and consumption networks are perhaps the single largest portion of capital and the most difficult to replace. Although utilities hold a large portion of the capital at risk, about $1.2 trillion invested in stationary sources, it is the rest of the energy infrastructure, an additional $1.6 trillion, that is also at risk from the environmental regulations.[10] This will have a larger impact on the economy if abandoned

Reactor Design

The reactor technology selected is, in the author's opinion the most mature design available, having undergone one review with the Nuclear Regulatory Commission.[11] PRISM is at the lower end of the needed temperature to be a viable candidate for coal gasification. Although not optimal, it is adequate and adequate is enough. PRISM is a modular design and offers a rail transportable version, Mod A, 425 MW(t) outer diameter 6.6 m (217 ft), and a larger version, Mod B, 840 MW(t) outer diameter 10 m (32.8 ft).[11]

The Department of Energy (DOE) is pursuing a high temperature gas reactor design, the Next Generation Nuclear Plant (NGNP) which can achieve gasification without aid.[12] The High Temperature Gas Reactor (HTGR), e.g. NGNP, is expected to be the only path forward for nuclear process heat.[13, 14] The problem with this design is the nuclear fuel cycle requires modification and significant expansion to enable large-scale market penetration. GE-H PRISM produces all nuclear fuel on site.[11] The needed nuclear fuel infrastructure is built as the plants are built removing a potential constraint for widespread deployment.

Table I. PRISM Reactor Parameters (Mod B)

Rx Power	
Net	311 MW(e)
Thermal	840 MW(t)
Core Temp	
Outlet	485 °C
Inlet	338 °C
BOP	
Steam	
Temp	452 °C
Pressure	147.2 bar
Flow	760 kg/s
Feed Temp	216 °C

Table I lists the reactor plant parameters. Of particular note is the steam temperature, 452°C. This is considerably lower than even the bottom end of the methenation processes of 600°C.[15] This problem was resolved using a S-CO_2 heat pump to amplify the reactor output temperature. The temperature amplifier is able to achieve 705 °C in the gasifier with no added oxygen. Assuming equilibrium conditions at the gasifier exit the theoretical H_2:CO ratio is 2.42 and has a higher heating value HHV cold gas efficiency of 111%. The addition of nuclear heat into the overall endothermic reaction upgrades the heat content of the coal into the final products.

Load Following

Nuclear reactors, like PRISM, can load follow and do so much better than fossil fueled power plants because reactor power follows steam demand with non of the vagaries of a boiler. Although load following is possible it is not desirable. There is a significant cost disincentive when reducing the overall capacity factor when in a dispatch mode. To allow full capital recovery and allow the plant to load follow the addition of thermal energy storage was incorporated in the design using a carbon copy of a solar thermal pilot plant's hot and cold salt flasks.[16, 17] The size of storage needed to allow peaking operation is roughly 4% of daily energy production, 408 MW-hr for a 425 MW(t) reactor. This amount of storage costs $26.4/kW(t) (2009 $) of installed capacity.[17]

The salt storage $NaNO_3$ and KNO_3 is inexpensive and is compatible with the liquid sodium coolant of the reactor block.[17, 18] The coolant compatibility eliminates the possibility of sodium-water interactions and simplifies the overall design. It also acts as a time buffer between transients in the process yard or electric yard from impacting reactor power. This benefit allows for remote dispatch capability along with voltage and frequency control delegated to the grid managers, a feature not enjoyed by conventional nuclear reactors.[a]

Overall Design and Modeling Considerations

Figure 1 shows a general conceptual design for the gasifier. A more detailed drawing and states are Appendix A. The design sought parsimony in the number and amount of heat exchangers to limit the overall capital cost and achieve operational reliability through simplicity, at the cost of overall thermodynamic efficiency. There was some optimization of the design, but only enough to achieve economic feasibility. Further design work can improve efficiency and improve cost competitiveness.

The design was simulated entirely in Engineering Equation Solver (EES) using built in thermophysical properties. The heat exchangers were approximated with fixed pressure drops and specified output Terminal Temperature Differences (TTD). These assumptions can be later removed with a more detailed design and optimized for capital recovery. Design of the heat exchangers was based off of discussions with Heatric sales people, information online and some published work.[19, 20]

Rudimentary pinch point analysis was done in portions of the system where there was a phase change or a significant change in specific heat capacities. A more rigorous pinch point analysis will require full scale modeling of the heat exchangers.

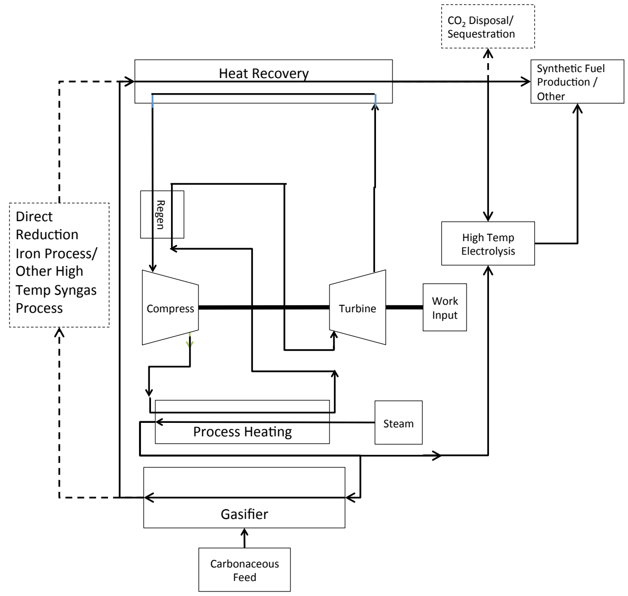


Fig. 1. Conceptual drawing of integrated heat-pump and gasifier.

Heat Pump

The most critical and enabling component of the design is the heat pump. The limiting component is the high-temperature high-pressure portion of the system. The temperature was set to 820°C and a pressure of 200 bar. This was based off of a design limit of 982°C and 313 bar @ 800°C for Heatric Alloy 617 heat exchangers.[19] The temperatures and mass flow rate of the gasifier were determined iteratively with the state of the gasifier and its material flow rates. Figure 2 shows the cycle diagram of the heat pump. The COP for the simple heat pump was 2.79.

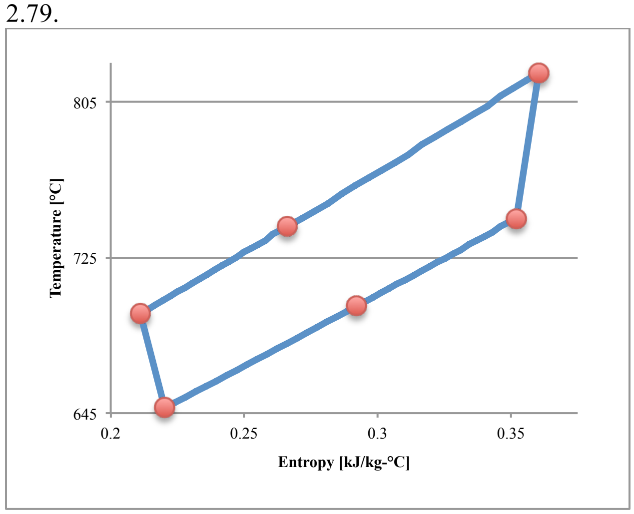


Fig. 2. Cycle Diagram of S-CO_2.

The heat pump is driven by a simple steam turbine with an overall cycle efficiency of 33.2%. This is a conservative design with no optimization and can readily be increased to 38% using steam, or replaced outright with a S-CO_2 heat engine with a nominal efficiency of 40%.[21-23] Later economic analysis used 40% efficiency because of the advantages of S-CO_2.

S-CO_2 undergoes a significant change in heat capacity close to the critical pressure, 73.1 bar, of the fluid and is the limiting constraint on efficiency in the S-CO_2 Brayton cycle.[23] The lowest pressure of the heat pump is 132 bar at the compressor suction, well above the critical pressure.

Gasifier

The gasifier is based on a dry ash Lurgi moving bed gasifier at 50 bar, with an exit temperature of 705°C.[15] This gasifier was selected mainly because of the lower operational temperature desired for minimal CO_2 production and maximum temperature of 815°C supplied by the steam to the gasifier. The gasifier is also well understood from a cost performance standpoint. Additionally, the lower operational temperature prevents slagging in the gasifier due to melting the ash.

The converted coal plant was broken down into 100 MW(e) blocks that ran at 85% capacity factor. This corresponded to a coal feed rate of 9.84 kg/s of 10,130 Btu/lb_m coal at 38% efficiency. This was a convenient basis as this is consistent with one 800 t/day Lurgi gasifier. Converting 500 MW(e) to NCtL requires 5 Lurgi gasifiers and one PRISM power block (two-840 MW(t) reactor modules or four-425 MW(t) modules).

The feedstock selected was a sub-bituminous coal similar to Powder River Basin coal. The ultimate analysis is listed in Table II. Other coal ranks were verified to achieve gasification temperatures but were neglected from detailed analysis for simplicity as sub-bituminous coal represents roughly half of all coal consumed in the United States.

Table II. Ultimate Analysis of Coal ($^{w}/_{o}$)

C	58.8
H_2	3.8
S	0.3
O_2	12.2
N_2	1.3
H_2O	19.6
HHV (Btu/lb_m)	10,130

The steam supplied to the gasifier serves as the primary method of heating. Boost oxygen, available as a byproduct from the high temperature Solid Oxide Electrolytic Cell (SOEC) is not necessary to achieve gasification. Only if it were desired to make the gasifier exothermic and shift the equilibrium would the boost oxygen be needed. The use of oxygen is not desirable as it reduces the fraction of methane and carbon monoxide in the product stream.

The gasifier was modeled using the law of mass action and the following four equilibrium reactions, equation (1). The gasifier was assumed to achieve equilibrium concentrations, effectively neglecting any kinetic effects. Further work will require relaxing this assumption. However, as an approximation it checks well with published information available on the product gas supplied by the gasifier.[15]

$$\begin{aligned} C + H_2O &\rightleftharpoons CO + H_2 \\ CO + H_2O &\rightleftharpoons CO_2 + H_2 \\ C + 2H_2 &\rightleftharpoons CH_4 \\ N_2 + 3H_2 &\rightleftharpoons 2NH_3 \end{aligned} \tag{1}$$

Other reactions such as the formation of carbonyl sulfide, hydrogen sulfide, and sulfur oxide production were modeled as the formation of hydrogen sulfide. The low sulfur content of the coal left the molar concentration of sulfur to be small compared to the other reactants. Thus for computational simplicity other sulfur compounds were neglected.

The gasifier feed is prepared as a coarsely ground slurry (3-40 mm) where a catalyst can be added.[15] The coal is prepared using the site's existing mechanical crusher, pulverized coal plants with the 200 and 50 mesh screens replaced with 6 mesh.[24] The catalyzed reaction allows the gasifier to more closely approach equilibrium and assumes that an increased fraction of methane is desired. If less methane is desired the catalyst may be omitted. The slurry from the exit was assumed to have a 30% moisture content and was sent to a dryer that reclaims heat from the char exiting the gasifier and heat from steam to dry the feedstock and raise it to 330°C. This temperature was selected to prevent de-volatilization of the feed.

The dryer is kept at a slight vacuum to remove steam and inert gases, but is at a low enough temperature to prevent devolitalization. The char then enters a retort where it is raised to 500°C in an oxygen depleted environment for partial direct liquefaction of the coal feed stock. If desired, hydrogen can be produced or taken from the stoichiometric excess of recycled hydrogen from the FT portion. Because of the cost of hydrogen (thermodynamic and monetary) no excess hydrogen was produced in this model. Hydrogen production effectively removed any economic advantage. If hydrogen were desired in large quantities integrating a steam methane reformer is the most cost effective approach.

The char is then sent to the gasifier for further reaction. The composition of the gasifier and retort discharges is listed in Table III as well as the overall energy inputs into and out of the combined system.

Quantities discharged from the retort were estimated using empirical relationships.[15]

The whole process of drying was to add as much heat as possible to minimize the heat taken from the S-CO_2 heat pump. This approach allows the gasifier to achieve a higher overall temperature. It can be omitted, but at the penalty of reduced gasifier temperatures.

Table III. Gasifier and retort discharges for a nominal (935 ton/day) gasifier

	kg/s	HHV MJ/s	
RETORT			
H_2	.01	1.1	
CO	0.17	1.7	
CH_4	0.20	10.9	
CO_2	0.27	–	
C_2H_6	0.07	3.8	
Liquids	0.77	35.6	
Total		**53.1**	
GASIFIER			
H_2	0.30	42.4	
CO	1.58	16.0	
CH_4	2.56	142.1	
CO_2	7.54	–	
NH_3	0.003	–	
H_2S	0.03	–	
N_2	0.13	–	
Total		**200.5**	
FEED			
Coal	9.84	231.9	
Reactor	–	348.6	
Total		**580.5**	
PRODUCTS			Price
Electricity		132.7	\$0.028/MJ
Diesel	1.32	60.1	\$0.022/MJ
Gasoline	0.23	11.1	\$0.024/MJ
SNG	3.17	165.8	\$0.0028/MJ
LPG	0.26	12.8	\$0.031/MJ
Butane	0.07	3.8	\$0.0028/MJ
NH_3	0.003	–	\$0.24/kg
H_2S	0.03	–	\$10.64/m ton S
Total		**386.4**	

The char is discharged from the gasifier with an estimated consumption of the carbon of 99.4% on a molar basis or 10% carbon by mass remaining in the discharge.

The NCtL was compared to a state-of-the-art dual stage gasifier.[25] The dual stage gasifier had a cold gas efficiency based on Lower Heating Values (LHV) of 80.1% compared to the modified cold gas efficiency NCtL of 88.3%. This was compared to the modified cold gas efficiency of another NCtL plant that reduced 90% of its CO_2.[12] The other NCtL approach had a modified cold gas efficiency of 65%. The difference between the NCtL approaches is the thermodynamic losses attributed to reducing the carbon dioxide and producing hydrogen. The ratio of carbon production to product mass was also telling 2.45 for the dual stage gasifier, 0.854 for NCtL design specified here, and effectively zero in the other NCtL design.[12, 25]

The electrolysis of water is energy intensive and was only done to the proportion needed to achieve the desired H_2:CO ratio to the Fischer-Tropsch reactor. As SOEC become more efficient and costs come down they can be incorporated as plant modifications. The main driving component on SOEC economics is the cost of electricity. Market prices for electricity will have to drastically be reduced in order for it to become economic to consume the electricity in the SOEC instead of selling it on the grid.

Solid Oxide Electrolytic Cell

There are several options for reducing CO_2, one option, a reverse gas shift reactor, was neglected from the design, because of the cost of producing hydrogen from SOEC. The other option is to integrate the hydrogen production and carbon dioxide reduction into one high temperature electrolysis plant.[26] This is the approach that was taken to evaluate economic feasibility.

The minimization of CO_2 production leads to a higher input of nuclear heat stored in the chemical bonds of the fuel effectively reducing the carbon intensity per ton of carbon mined while maximizing the output product.

There are Solid Oxide Fuel Cells (SOFC) that are commercially available near the MW scale and operate at about 800°C. Bloomenergy offers a 200 kW design.[27] To convert a 100 kW(e) coal plant it would take 2 of these energy servers to produce the requisite hydrogen. A SOFC is exactly like a SOEC except the transport of oxygen across the plate is reversed due to the change in mass flow rates and polarity on the machine. The design assumed the fuel cells were placed in pressure housing and a slight vacuum drawn on the oxygen side to lower the required current to the system. The SOEC was assumed to convert 70% of the water fed into it into product gas.

The minimal use of SOEC's in the design is the primary cost and thermodynamic differentiator between this design and the other NCtL plants.[12] When economic modeling was done, the cost of converting all of the carbon dioxide into carbon monoxide and produce enough hydrogen was about 2-3 times the cost to what the market could support.

Although technologically feasible, full or even partial carbon dioxide reductions were omitted. Instead, the preferred course of action is to sequester the CO_2 produced or emit it directly to the atmosphere. Since the regulations are so stringent for emissions, direct emission was taken as a non-starter.

The SOEC was integrated directly with the design and the steam used in electrolysis was taken directly from the discharge of the heat pump at 50 bar and 815°C. The oxygen side pressure was reduced by 10 bar to aid in reducing the potential across the cell.

The fuel cell was assumed to have an efficiency of 80%, ratio of the ideal cell potential to the actual. The ideal cell potential was given by the change in Gibbs free energy of the system.[26]

Fischer-Tropsch Synthesis

The Fischer-Tropsch Synthesis (FT) portion was not modeled in detail. As the gasifier is a Lurgi dry gasifier, the author used Table 6.9 and Table 6.11 of Synthetic Fuels approximated the entire FT process.[15] Thermodynamic loss form the FT process, 562 MW(t) was approximated by a portion of steam being extracted from the reactor steam generator, 133 MW(t), and then requiring the difference to be made up by the reactor.

The FT output liquids and gases were taken as a ratio of the higher heating values. The gases were evenly split between LPG and methane. The ratio of the liquids was approximated by 5.7:1 diesel to naphtha by mass. This large difference is due to the heavy liquids from pyrolysis being sent to the FT hydrocracker.

Summary

The feed from each Lurgi gasifier produces 900.9 bbl/day diesel, 181.3 bbl/day naphtha, 13,576 MMBtu/day SNG, 1,052 MMBtu/day LPG, and 675 metric tons CO_2 per day. The net electrical output from the station is 133 MW(e), 33 MW(e) recovered from FT and 100 MW(e) from the original steam plant.

Part II: Economic Assessment

The economic model was split into two parts. First is the revenue generated by the sale of the products, Levelized Value of Heat (LVOH) and second is the levelized cost of producing each unit sold. A comparison was made between the two. If the quantities were close then the costs were justified. The economic analysis included no subsidies or even loan guarantees to verify long term economic sustainability as tax code spending is a politically volatile issue.

Levelized Cost Analysis

The model used was derived directly from one used by the Congressional Budget Office.[28] The key difference with this model compared to more generic levelized cost models is the rate of return of capital is a function of the risk associated with the project measured by the amount of equity in the project. As equity is repaid the amount of risk associated with the project is reduced.[28]

The LVOH was determined using the output information from the model on the energy content of all products (or mass for the non-heat producing products). The market assumptions were based off of using decadal averages. The prices were set to \$3.00/gal for diesel and gasoline (naphtha) \$4.00/gal for LPG, \$3.00/MMBtu for SNG and butane. Table III lists their calculated values.

The model assumed 45% debt financing at a rate of 8%, and that the owner would be a merchant generator, the sale of the majority of the projects would be in deregulated markets. The nominal cost of equity was determined by setting the return on products by using the LVOH. The model had an overall 12.7% return on all capital invested. The peak cost of equity was 16.3% with a nominal return of 13.5%.

A scenario was also run to see the impact of using a CC plant to produce electricity and the smallest possible nuclear plant to supply the heat for coal liquefaction. The entire FT train had an overall 16.5% return on all capital invested. The peak return of investor equity was 23.0% with a nominal return of 17.9%. The CC plant had a return on equity of 28.6%. When NCtL FT train was combined with the CC plant, the combined project had a rate of return on equity of 23.8%.

Modeling the Costs

The physical model described in the previous section provides the cost per MW-hr of useful work generated at the site. The construction and fixed Operations and Maintenance (O&M) costs were referenced to the nameplate capacity, rate of producing useful work, in MW. Useful work was defined as the higher heating value of the consumable gases and liquids and electricity. This also included ammonia and sulfur. More generally, useful work is a salable product. For the sake of this definition carbon dioxide, char and mercury were considered a waste products requiring disposal. All fuel costs, except nuclear, were included in LVOH. Nuclear was treated separately because of its unique cost characteristics that arise from how it is regulated and legal requirements for fuel disposal. The nuclear model relied exclusively on data provided by the CBO.[28]

Determining the construction costs, fixed O&M, and variable O&M required some estimation. The primary source of information was the Energy Information Agency (EIA) Annual Energy Outlook 2012 (AEO 2012).[29] To estimate the costs of each component every cost was referenced to input of thermal heat from the representative fuel source instead of electrical output. For the gasifier and the Carbon Capture Sequestration (CCS) the costs were based off of the IGCC and the IGCC-CCS fractional costs, respectively.

The SOEC was approximated using the Fuel Cell costs. The fuel cell costs were not normalized using the heat rate. Because they are providing the same role just reversed the cycle efficiency would cancel out. The power output of the fuel cell was reversed and taken to be the power input needed for electrolysis and was then divided by the total useful power output of the facility.

The values for the FT plant were taken from National Energy Technology Laboratory (NETL) estimates,[30] and adjusted for inflation using the Consumer Price Index to reference year dollars (2009 $). The values were determined using the HHV of the product outputs from the NETL report to reference the total overall costs listed in the executive summary. The quantity was multiplied by the HHV of the products from NCtL and divided by the total site useful work/power as appropriate.

The cost of the reactor technology was estimated in a similar fashion to the IGCC model (the fractional cost was taken as 100%). The difference is the reactor technology listed in AEO 2012 is for a large Light Water Reactor (LWR) similar in design to the AP-1000. The reactor used in NCtL is a modular factory built unit that is shipped to the site via rail and is a pool type Sodium Fast Reactor (SFR). The complexities of deriving an entire cost estimate for the Small Modular Reactor is very difficult. Typically, SFR's estimated cost is about 1.3 to 1.5 times than of a similarly sized LWR. This was included in the price and then subtracted out again as credit for reusing the existing turbine building and transmission infrastructure, along with less power going to the steam plant (25% going to process heat). An additional $200/kW was added to account for thermal energy storage (4% of the heat needed for the dedicated electric plant). The stored energy will allow the plant to load follow without reducing the energy produced by the reactor. This allows the reactor to operate with a 90% capacity factor and provide fully dispatchable power.

The significance of incorporating the salt storage is a fault on or in one component is isolated to that component. It allows the steam electric plant to be down for maintenance while producing synthetic fuels. In a multi reactor complex it allows one reactor to be down while the other provides heat to loads determined by the utility. The overall effect is to raise the capacity factor for the site by reducing the Effective Force Outage Rate (EFOR). As a conservative estimate the average capacity factor for the entire facility was taken as 87%.

To simplify the calculations and integrate with the existing CBO model all of the traditional nuclear costs were broken out and multiplied by the ration of the useful work to the heat input from the reactor. This is called η_{Rx} and was calculated as 111% for the nuclear only conversion and 325% for the combined CC and nuclear conversion. It was used to replace the thermal efficiency of the plant in the nuclear fuel costs and to scale the unique nuclear costs to the output of the plant using the same approach as used for determining the overall plant costs. As a result of this detail, the more specific CBO variable O&M costs were used, and are $0.48/MW-hr.[28] For conservatism the AEO fixed O&M costs were used as SFR O&M costs are expected to be lower because of the elimination of much of the complexity in the plant, no injection systems and reactor has no moving parts, and coolant material compatibility (LWR suffer from corrosion issues with the use of boric acid in the coolant).[11, 29, 31, 32]

The incremental capital costs were taken from the CBO report for the different technologies. The FT incremental capital costs were estimated at $6,000/MW and $12,000/MW for the less than 30-years and greater than 30-years scenarios. The cost fraction was determined in a similar manner to the fixed O&M calculations. The nuclear only NCtL had values of $7,109/MW and $12,974/MW respectively. The NCtL FT only had values of $5,977/MW and $10,113/MW respectively.

Table IV breaks down the costs of each component in analyzed in the system. The overnight cost of $1,992/kW is unusual for a nuclear system. This is not an anomaly. Nuclear reactors are expensive and fast reactors are even more expensive. However, this design is not limited to the traditional thermodynamic efficiency of electricity generation ~32% for LWR and 37% for SFR. This thermodynamic efficiency is the useful work output, electricity to the reactor heat input. In the cogeneration mode specified here the useful work output is 346% higher for every joule of heat from the reactor. This results in an overall thermodynamic efficiency of 66%.

By minimizing the production of carbon dioxide as a fundamental design goal, this plant has lower operational costs and higher revenue than other designs. The NETL design, which has the most detailed and recent cost estimates has an overnight cost of $1,346/kW (2009 $). The NCtL design here costs $1,992/kW (2009 $). Because the NCtL does not rely on the sale of one particular good, instead producing a diverse set of products, it will be less susceptible to market volatility in any one market. It produces 170 MW of natural gas, 84 MW of liquid fuels, and 133 MW(e), with revenue divided roughly evenly between each product stream. The other benefit of NCtL is 60% of the heat comes from a fuel source costing $0.75/MMBtu compared to using coal or natural gas which cost $2.38/MMBtu and $4.48/MMBtu respectively.[29]

Table IV. Cost estimates for a nominal NCtL plant.

	C^{overn} $/kW	$C^{fixed\ OM}$ $/kW	$c^{var\ OM}$ $/MW-hr	Cost %
FT Portion of Nuclear and CC Conversion				
Gasifier	482.8	8.88	1.03	52.46
CCS	194.2	2.515	0.324	21.10
SOEC	9.0	4.607	0	0.98
PRISM	164.5	2.713	.0149	17.87
FT Plant	69.9	19.93	0.1744	7.59
Total	**920.4**	**34.503**	**1.544**	
All Nuclear Conversion				
Gasifier	357.9	6.583	0.7638	17.97
CCS	144	1.865	0.2405	7.23
SOEC	6.669	0.3416	0	0.34
PRISM	1413	23.32	0.1276	70.95
FT Plant	69.91	19.93	0.1744	3.51
Total	**1,992**	**52.038**	**1.306**	

Cost of Repowering a Coal Plant

GEH markets the PRISM reactor as a two-unit power pack. The power pack has a thermal power of 1,680 MW(t) (two 840 MW(t) reactors). Using this number and η_{Rx} the site produces 1,861 MW of salable product. This replaces outright 481 MW(e) of the coal plant. The cost of replacing 481 MW(e) is $3,707 million.

This may seem like a significant amount, to replace just the 481 MW(e) with IGCC-CCS – $2,543 million, natural gas fired CC – $465 million. These numbers do not include the capability of generating additional revenue from the sale of liquid fuels and natural gas. For a CC plant to generate comparable revenue it would need to triple its electricity generation; costing $1,395 million, in a market that is already well serviced with a fuel source that is 644% more expensive. It also forces the utility to write down all of its existing coal plants reducing their market competitiveness.

The other option is to take a hybrid approach and use the CC to meet the electricity demand and the reactor to only service FT synthesis. A single Mod A core would liquefy the coal of a 481 MW(e) coal plant and would cost $1,270 million. The total project would cost $1,735 million. The average cost of conversion, referenced to the original capacity factor of the coal plant is $3,608/kW(e). Using the 425 MW(t) Mod A core, this is the smallest expenditure possible. There are smaller reactors available ranging from 30, 80, to 300 MW(t) roughly corresponding to one, two and three 800 t/day Lurgi gasifiers respectively. This technology concept is fully scalable and modularly constructed to meet the utilities specific needs.

This project will yield a much higher return on equity than all of the others combined. However, this higher return (19.3% on NCtL and 26% on the CC) comes at the risk of being exposed to future environmental regulations on the combustion products form the CC plant. The nuclear only NCtL has a 13.4% return on equity, with less future regulatory risk, but carries a higher risk of less than acceptable returns due to fuel price fluctuations.

Revenue from Repowering a Coal Plant

Figure 3 and 4 show the net annual revenue for the utility and the combined state and federal taxes. The cost estimates used in making these figures were those listed in Table III. The profits that are possible with current market prices are above those listed. The use of decadal averages shows how independent an acceptable rate of return, 13.4%, is on commodity price volatility.

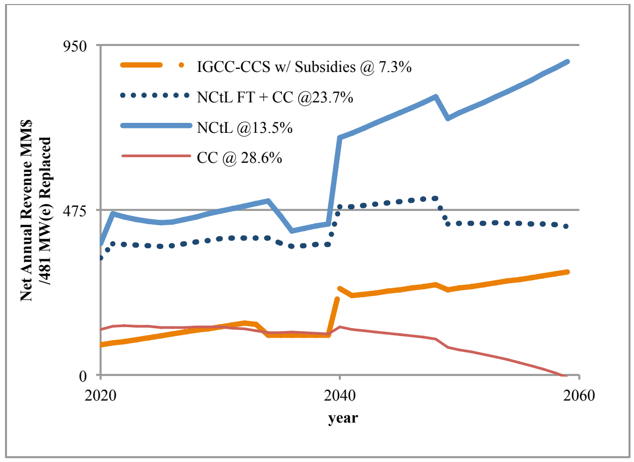


Fig. 3. Comparison of annual revenues for NCtL and EIA estimates for CC and IGCC-CCS plants.[29]

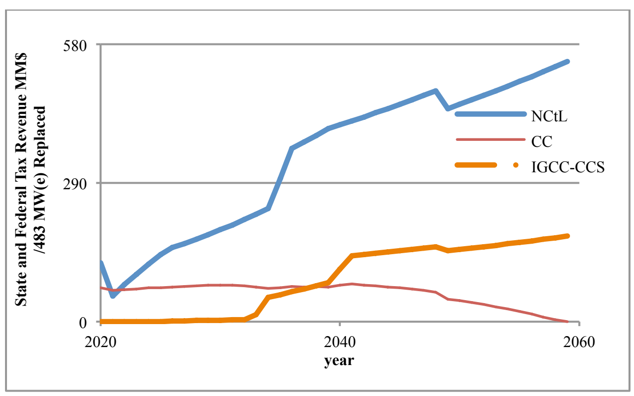


Fig. 4. Comparison of combined annual state (4%) and federal (35%) tax revenues for NCtL CC and IGCC-CCS.

FUTURE WORK

The technology of NCtL leverages the strengths of each component. This process can be further integrated with other technologies. Three key future expansions are integrating municipal garbage plasma incinerators, iron ore reduction, and using natural gas as a feedstock through steam methane reforming. Other work includes refining cost estimates and the author's current research on thermal energy storage.

The plasma garbage incinerators are perhaps the most interesting. They produce a synthetic gas that is readily suited for a liquefaction process. Current thought on these is to produce electricity. However we have shown here how valuable carbon is as a gas or liquid fuel. The location of coal plants make them especially suited for handing a city or metropolitan areas entire garbage stream without using landfills. It allows domestic reclamation of rare earth metals from our garbage along with other metals such as aluminum, iron, copper and nickel. Industrial recycling can hopefully close the material loop on the economy. The incinerators can also be used to process the fines made by pulverizing the coal.

The synthetic gases, particularly the carbon monoxide is especially suited for direct reduction of iron, e.g. the Midrex process. DRI offers a way of producing domestic iron of a superior quality and low price with little to no environmental impact.

The location of the rail lines and large rail yards facilitates the delivery of large volumes of material such as coal, garbage, iron ore, and bauxite. The colocation of other industries on the utilities land provides additional benefits such as revenue from leases and an expansion into more markets. NCtL is a gateway technology and is only limited by the imagination and how much one is willing to spend.

CONCLUSION

Coal, if left solely in the role of producing electricity, cannot compete in future markets. If it is used, on its own or with natural gas, to produce liquid fuels it is competitive, however it is limited by increasingly more stringent carbon dioxide regulations. For coal to have a meaningful future in this country or world for that mater, it needs to be integrated with other technologies.

As a political sell, NCtL has many desirable points:

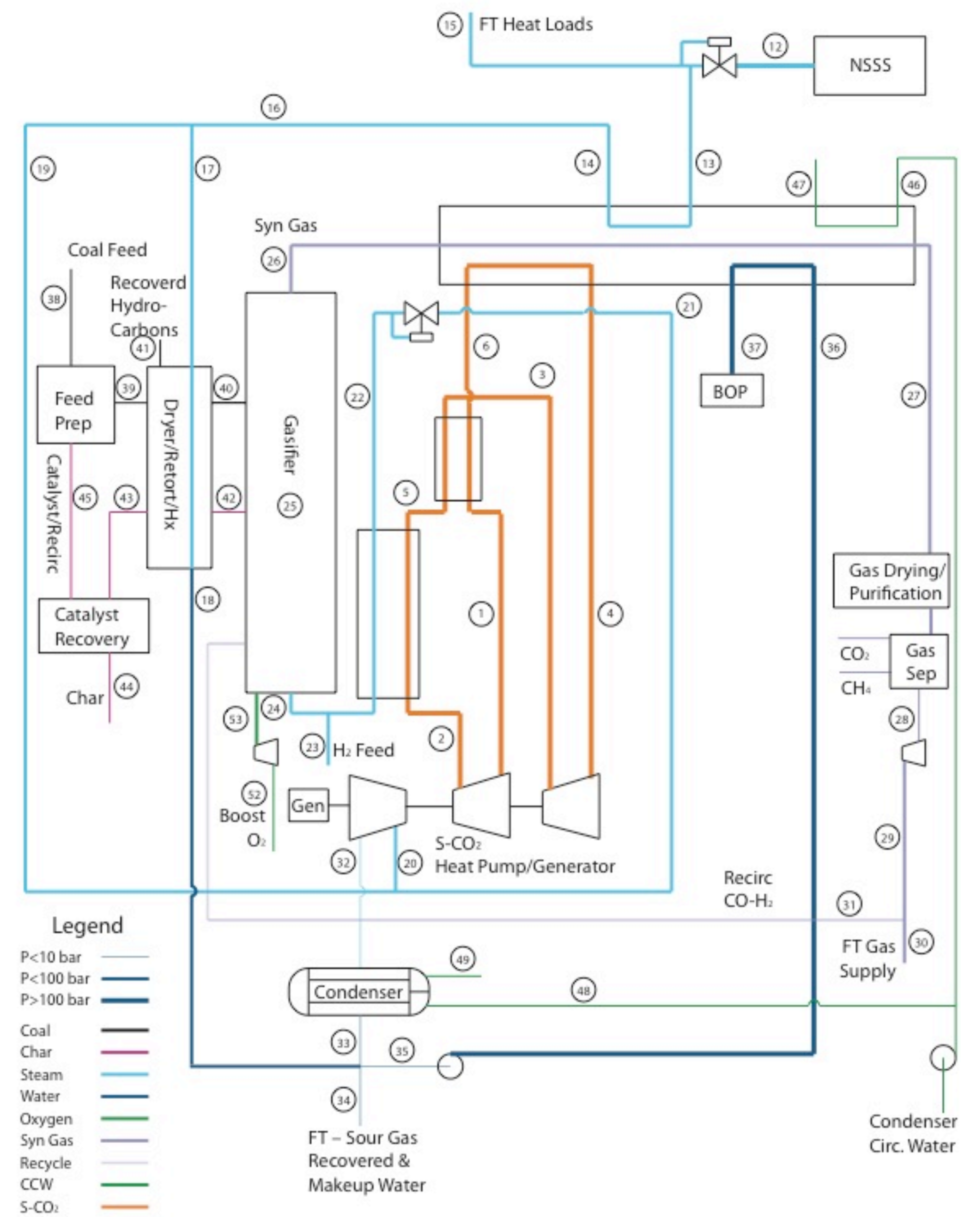
- NCtL is tax revenue positive
- No tax code spending
- No government assistance
- Secures our energy independence
- C**reates** new industries and jobs, **saving** the jobs that we already have.
- Reduces overall carbon dioxide emissions

The path with the highest revenue generation detailed here relies on each of the major fuel sources, coal, natural gas, and nuclear, each in an optimal configuration. It provides a path forward with a capital investment of $1,735 million to replace 481 MW(e) of coal generation. It allows the utility to sell energy in three markets, electricity, pipeline gas, and transportation fuels. It also provides a tremendous opportunity for a utility to expand into other markets as technology and capital develop.

There is nothing inherently bad about coal. In fact, this paper hopefully served to show just how valuable coal could remain.

APPENDIX A: STATE DIAGRAM AND PARAMETERS.

#	T [°K]	P [Bar]	m [kg/s]	#	T	P	m	#	T	P	m	#	T	P	m
1	298.2	1.013		17	853.8	65	44.84	28	313.2	48.28	17.28	42		1.846	
2	1018	132.6	65.89	18	853.8	65	3.72	31	403.2	22		43	978.2	0.4321	
3	1093	200		19	443.8	61	3.72	33	331.9	0.1881		44	325.2	0.4321	
4	969.3	196		20	853.8	65	41.12	34	329.9	0.1881	29.26	45	298.2	0.4321	
5	921.1	136.6		21	853.8	65	29.26	35	298.2	1.013	11.9	46	298.2	0	
6	1014	198		22	853.8	65	11.86	36	331.1	0.1881	44.88	47	298.2	2.047	17.17
7	973.2	134.6		23	849	52	11.86	37	333.7	148.2	44.88	48	327.2	1.013	
13	725.2	147.2	44.88	24	1088	50	0.1997	38	547.3	147.2	44.88	49	298.2	2.047	528.3
14	673.9	65.69	44.84	25	1088	50	11.66	39	298.2	9.821		50	328	1.013	
15	853.8	65	44.84	26	978.2	50	17.28	40	298.2	10.26		53	298.2	1.3	0
16	673.9	65.69	0.04365	27	978.2	50	17.28	41	773	6.049		54	801.7	50	0



NOMENCLATURE

$^w/_o$ = weight percent
(e) = electric
(t) = thermal
AEO = Annual Energy Outlook
AP-1000 = Westinghouse 1,154 MW(e) LWR
bbl = barrel of oil (42 gallons US)
C^{overn} = overnight cost [$/kW]
$C^{fixed\ OM}$ = fixed O&M costs [$/kW]
$c^{var\ OM}$ = variable O&M costs [$/MW-hr]
CBO = Congressional Budget Office
CC = Combined Cycle (natural gas fueled)
CCS = Carbon Capture Sequestration
CCW = Condenser Circulating Water
COP = Coefficient of Performance
CtL = Coal-to-Liquids
DRI = Direct Reduced Iron
EES = Engineering Equation Solver
EFOR = Effective Forced Outage Rate
EIA = Energy Information Agency
EPA = Environmental Protection Agency
η_{Rx} =Useful work output/ reactor thermal power
ft = feet
FT = Fischer-Tropsch
GE-H = General Electric – Hitachi
HHV = Higher Heating Value
hr = hour
HTGR = High Temperature Gas Reactor
IGCC = Integrated Gasification Combined Cycle
kg = kilo-gram
kW = kilo-watt
lb_m = pound mass
LHH = Lower Heating Value
LPG = Liquid Petroleum Gas
LVOH = Levelized Value of Heat
LWR = Light Water Reactor
m = meter
MMBtu = Million British Thermal Units
MW = Mega-watt
NCtL = Nuclear Coal-to-Liquids
NGNP = Next Generation Nuclear Plant
O&M = Operations & Maintenance
PRISM = Power Reactor Innovative Small Module
S-CO₂ = Supercritical carbon dioxide
SFR = Sodium Fast Reactor
SMR = Small Modular Reactor or Small and Medium Reactors
SNG = Synthetic Natural Gas
SOEC = Solid Oxide Electrolytic Cell
SOFC = Solid Oxide Fuel Cell
TTD = Terminal Temperature Difference

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ENDNOTES

[a] These capabilities are the subject of the author's current research and are as yet unpublished.