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ORIGINAL PAPER

Market sensitivity of solar–fossil hybrid electricity generation to price, efficiency, policy, and fuel projections

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Abstract
Ideally, new electricity-generating units will have low capital costs, low fuel costs, minimal environmental impacts, and satisfy demand without concerns of intermittency. When expanding generating capacity, candidate technologies can be evaluated against criteria such as these. Alternatively, it may be possible to pair technologies in such a way that the combination addresses these criteria better than either technology individually. One such approach is to pair concentrated solar power and natural gas combined cycle units. This paper analyzes how an integrated solar combined cycle (ISCC) facility could fare in the larger US electricity production market, although the results are generalizable to a wider range of technologies. Modeling results suggest that a critical consideration is the extent to which ISCC qualifies as being renewable under state-level renewable portfolio standards (RPSs). The technology would be utilized at a higher level if it fully satisfies an RPS; however, even if the technology does not satisfy an RPS, it would be market-competitive if optimistic goals for capital cost and avoided natural gas purchases are met. Furthermore, if used in parts of the country with strong solar resources, ISCC could produce as much as 14% of national electricity generation in 2050. Whether adoption of ISCC leads to reduced air pollutant and greenhouse gas emissions is dependent on the technologies, it displaces. Under default assumptions, the new ISCC capacity primarily displaces renewable and natural gas facilities as opposed to facilities with higher air-pollutant emissions. Thus, the air pollution benefits of ISCC may be limited.

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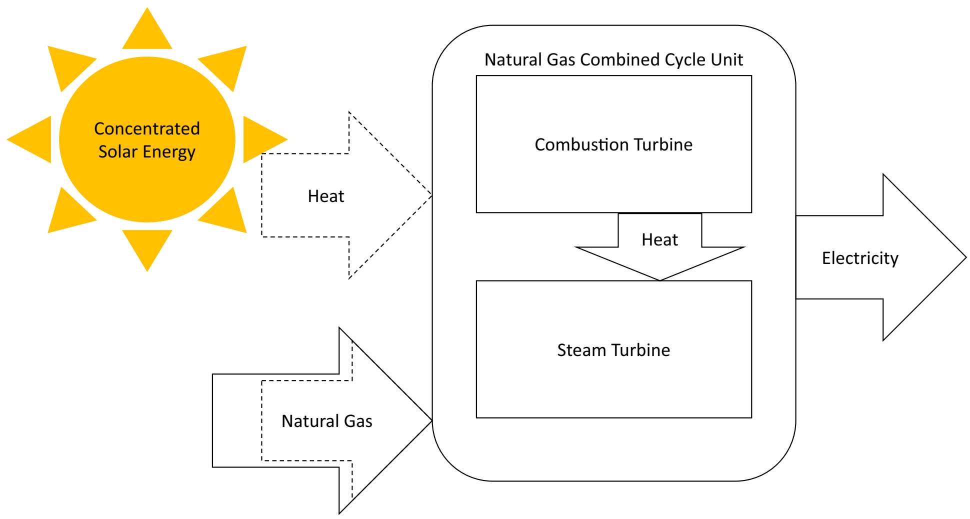
Graphical abstract



Keywords ISCC · Electricity generation · RPS · Solar · Natural gas · Renewable

Abbreviations

CHP	Combined heat and power
EPAUS9r	EPA's United States 9 region database
ISCC	Integrated solar combined cycle
MARKAL	MARKet ALlocation, an energy-economic model
MSW	Municipal solid waste
NG	Natural gas
NGCC	Natural gas combined cycle
RPS	Renewable portfolio standards
O&M	Operation and maintenance
PR	Partially renewable (some ISCC generation satisfies RPS)
FR	Fully renewable (all ISCC generation satisfies RPS)
NR	Not renewable (no ISCC generation satisfies RPS)
WTE	Waste to energy

Introduction

New electricity production capacity will need to be built over the next several decades. Considerations when new electricity infrastructure is built include investment and operating costs, reliability, emissions of various pollutants, fuel costs, and predictability of the fuel supply (Dong et al. 2013; Unsihuay-Vila et al. 2010). A variety of candidate technologies are available, each with benefits and drawbacks. Pulverized coal boilers and natural gas combined cycle (NGCC) units are proven technologies capable of providing reliable power to the grid. However, extraction, production, transmission, and combustion of fossil fuels generate air pollutants and greenhouse gas (GHG) emissions (EPA 2015).

Alternatively, solar and wind generation are now cost-competitive with fossil fuels in many parts of the country (EIA 2016). Solar and wind technologies limit exposure to fuel price fluctuations and do not emit air pollutants during operation. However, capital costs of these technologies would be affected by the supply and demand of materials such as carbon fiber, silicon, and rare earth metals (Vesborg and Jaramillo 2012). Furthermore, there would be emissions from obtaining these materials and during manufacturing. Also, both solar and wind technologies produce intermittent power which must be addressed through redundancies, energy storage, or the use of natural gas turbines to supplement generation during low output (i.e., no wind or sunshine). Understanding the trade-offs involved in alternative electricity production technologies is important for ensuring that our future electricity supply is cost-effective, sustainable, and reliable. While energy production technologies differ with respect to these and other attributes, it is important to note that the electric grid is fed by a portfolio of technologies and that this portfolio is designed to take advantage of the strengths and weaknesses of each technology.

For example, electric grids typically consist of baseload, shoulder load, and peaking technologies. Technologies within each of these designations are dispatched differently to meet societal electricity demands. Coal and nuclear power are baseload technologies that typically are most cost-effective and efficient if operated at steady levels. NGCC units are increasingly being used for baseload power but can be ramped up and down to meet shoulder loads, which include much of the additional energy demands during the day. Standalone natural gas combustion turbines (NGCTs) are less efficient than NGCC units, but their output can be ramped up and down almost instantaneously. Thus, standalone NGCTs are used for meeting peak load conditions during the day.

While currently representing only a combined 8% of national electricity generation annually (EIA 2017), wind and solar capacity is increasing dramatically. Many recent studies (e.g., Hirth et al. 2015; Muttqi et al. 2017; Schaber et al. 2012) address issues of large-scale wind and solar integration and the effects of these technologies on grid operation. Neither is a flexible technology, meaning their output cannot be modulated readily to follow electricity demands. Solar photovoltaics (PV) produce electricity primarily during the middle of the day. When there is a mismatch between peak demand and renewable generation, the net load is described as a “duck curve” (Denholm et al. 2015), which may require fossil plants to ramp quickly.

Adding renewables to the electricity mix can reduce long-term electricity prices, but these changes, particularly additional wind, have the potential to increase price volatility due to their variable nature (Kyritsis et al. 2017). Thus, large-scale deployment should also consider measures for addressing variability. Some technology options, such as concentrated solar power (CSP), include integrated storage mechanisms. Alternatively, stationary storage, whether batteries, reverse hydro, or some other mechanism, may be employed, albeit at an additional cost.

Policy constraints can also affect electricity generation. Wiser et al. (2017) have evaluated the impact of increased renewable electricity from strong renewable portfolio standards (RPSs). These standards define requirements for a certain fraction of electricity to come from a set of technologies identified as renewable. They found that RPSs are likely to increase the cost of the electric system; however, when accounting for the avoided externality cost due to improved air quality, there can be a net benefit of RPS.

Another option is to colocate electricity production technologies with characteristics that complement each other’s weaknesses. For example, CSP generation can be paired with NGCC units to form integrated solar combined cycle (ISCC). The heat generated via solar can displace some of the fuel demands while also taking advantage of the same equipment, grid connection, and labor. Increasing output from the NGCC portion of the facility can compensate at times of poor solar insolation. Antonanzas et al. (2014) and Spelling and Laumert (2015) evaluated several ISCC configurations. Alqahtani and Patino-Echeverri (2016) estimated the levelized cost of ISCC and compared their cost with other generation options. Barigozzi et al. (2012) and Spelling and Laumert (2015) identified an economically favorable ISCC technology configuration.

These prior studies have examined combined solar–gas technologies from the standpoint of their market competitiveness. However, they calculate competitiveness using levelized cost of energy (LCOE), which does not account for the interaction of the technology within the energy system. Furthermore, since ISCC is not yet a widely used technology, its cost and level of avoided natural gas use are uncertain. This uncertainty complicates the calculation of a single LCOE value. Evaluating competitiveness is one of the goals of our analysis. Net air pollutant and GHG emissions impacts of this technology are also estimated across the entire energy system. This emissions endpoint is more difficult to evaluate since it involves not only estimation of cost and market penetration but also depends on which technologies and fuels are being displaced (which may, in turn, be affected by policies and contextual assumptions) and on any additional cascading effects in the energy system. For example, a scenario that increases the price of electricity may result in industries opting to generate their own electricity via combined heat and power (CHP) systems, which in return influences the system-wide emissions.

Methods

There are several possible configurations for ISCC. The modeling in this paper is impacted only by cost and solar contribution and therefore could be representative of any ISCC configuration with similar parameters. A range of feasible parameters was obtained from Barigozzi et al. (2012) and Spelling and Laumert (2015). A generic ISCC configuration is represented in the schematic diagram in Fig. 1. Although this type of project is, in principle very promising capital costs are higher than standard NGCC units, which could be a barrier toward adoption.

MARKet ALlocation (MARKAL), an energy-economic optimization model, (Loulou et al. 2004) is used within a parametric sensitivity analysis (Saltelli et al. 2008) to evaluate a range of assumptions about the price of natural gas and the cost and efficiency of ISCC. For each model run, the market penetration potential and net system-wide energy and air pollutant and GHG emissions implications of ISCC are assessed. This technology assessment approach was previously used to evaluate solar photovoltaics (PV), coal and biomass with liquid fuels and electricity, and carbon capture and sequestration for NGCC (Aitken et al. 2016; Babaee and Loughlin 2018; Loughlin et al. 2013).

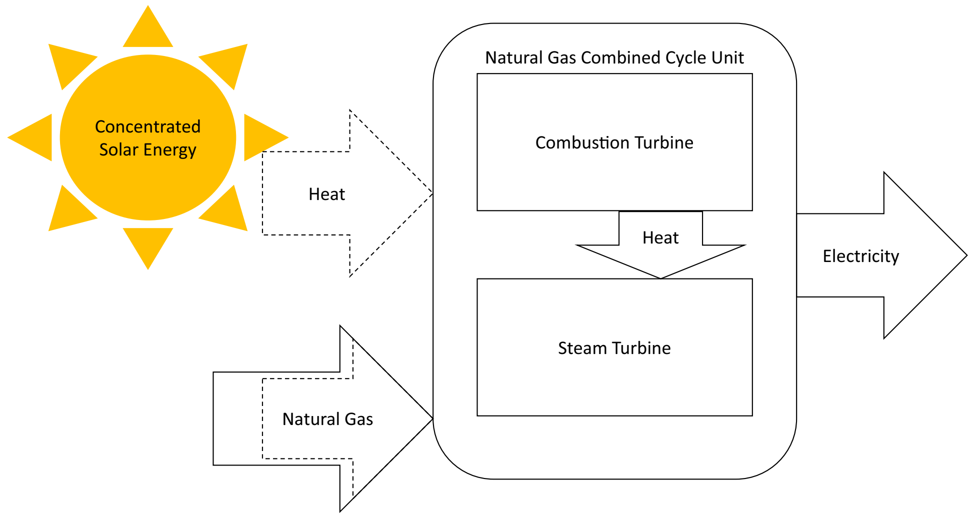


Fig. 1 Concentrating solar integration into an NGCC unit. The NGCC unit always has natural gas as an input and electricity as an output. When heat from the CSP is added as an input, less natural gas is required to produce the same quantity of electricity, which is represented by the dashed arrows

The MARKAL model

MARKAL is a linear programming-based optimization model that seeks to identify the set of technologies and fuels that meet societal energy demands over time, while simultaneously satisfying constraints such as limits on emissions (Loulou et al. 2004). For a given modeled scenario, MARKAL can track air pollutant and GHG emissions, as well as energy-related water use.

MARKAL is paired with the EPAUS9r_v16.1.1 database (Lenox et al. 2013) for this assessment. EPAUS9r_v16.1.1 characterizes the fuels, technologies, and projected energy demands of the US energy system over the period from 2005 to 2055. The database covers energy use in the residential, commercial, industrial, and transportation sectors as well as resource production and electricity generation. Spatial resolution is at the level of the US Census Divisions, hereafter referred to as regions. Technology and fuel market penetrations for these sectors in 2010 are calibrated to the 2016 Annual Energy Outlook (EIA 2016). Upstream emissions for all fossil fuels are included in the database (Lenox et al. 2013).

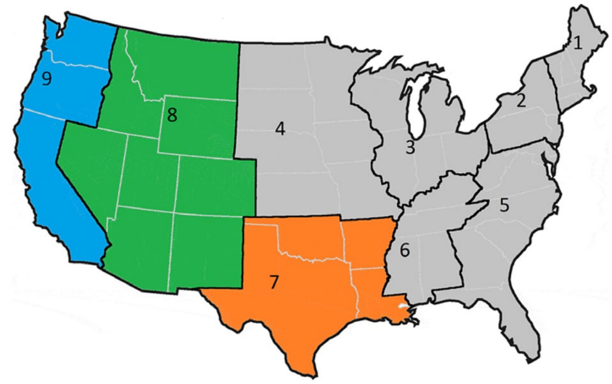
Regional energy service demands, which include lighting, space heating, and transportation, are derived from the AEO reference case demands (EIA 2016). Energy service demands can be satisfied by end-use technologies, such as lightbulbs, space heaters, and vehicles. In most instances, the model can choose from alternative versions of each technology, which differ by cost, efficiency, and often type of fuel. MARKAL's perfect foresight optimization routine, based on linear programming techniques, identifies the least cost technology and fuel choices over the remainder of the modeled time horizon, in 5-year time steps and given various energy balance constraints and emissions limits. Thus, these technology and fuel choices are endogenous to the model.

Technology choices are affected by factors such as existing technology stock and stock turnover, regional energy resources, and constraints on greenhouse gas and criteria air pollutant emissions. The Cross State Air Pollution Rule (CSAPR), the Corporate Average Fuel Economy (CAFE) standards, and Renewable Portfolio Standards (RPSs) are represented as constraints. RPSs, which have been specified by many states, are approximated in our regional model by estimating equivalent regional constraints calculated as weighted averages based on the percentage of a region's electricity generated by each state. These RPS-based constraints can vary considerably by region. The most stringent existing RPS is for Region 9 (Pacific including California, Washington, and Oregon), requiring nearly 30% of electricity from renewable sources starting in 2025. In contrast, Region 8 (Mountain including Nevada, Montana, Idaho, Wyoming, Utah, Colorado, Arizona, and New Mexico) requires 18% renewables, and Region 7 (West South Central including Texas, Oklahoma, Arkansas, Louisiana) requires only 10% in the same timeframe.

To apply MARKAL to assess a new technology, the availability, cost, and efficiency of the technology are first characterized and input to the MARKAL database. The MARKAL model then determines the resulting market penetration, fuel use, and displacement of competing technologies through time. Emissions impacts can also be evaluated, including primary impacts (emissions of the technology itself), secondary impacts (changes in the emissions of competing technologies), and tertiary impacts (changes due to cross-sector interactions that would result from fuel price changes and competition for fuels among sectors).

For this assessment, a representation of the ISCC technology was added to the database in Regions 7, 8, and 9. These regions correspond to the West South Central, Mountain, and Pacific US Census Divisions, respectively. Figure 2 shows the states in each region, and the regions in which

Fig. 2 The MARKAL regions with colors added to highlight the regions in which ISCC is modeled. The hybrid technology is available only in Regions 7, 8, and 9, which represent the West South Central, Mountain, and Pacific Regions of the country, respectively



Region	Name
1	New England
2	Mid Atlantic
3	East North Central
4	West North Central
5	South Atlantic
6	East South Central
7	West South Central
8	Mountain
9	Pacific

ISCC is modeled. The assessment of ISCC is limited to these regions because their solar resources and available land result in more favorable conditions than in other regions. ISCC is modeled as being available within these regions starting in 2020.

Technology assessment methodology

There is considerable uncertainty in the real-world cost of ISCC and in how much fuel it will save. There is additional uncertainty in future fuel prices, and how those fuel prices will affect technology adoption. Policy uncertainty, particularly in the stringency and technologies included within future RPSs, may also impact the use of ISCC. A benefit of the nested parametric sensitivity analysis (Loughlin et al. 2013) approach is that specific estimates of cost and fuel savings do not need to be specified a priori. Instead, through a series of nested parametric MARKAL model runs, market penetration and implications for wide-ranging combinations of assumptions about ISCC cost, fuel displacement, and the degree to which ISCC satisfies an RPS can be evaluated. The results provide an indication of market penetration potential if various performance targets are achieved, simultaneously considering fuel prices and alternative policy implementations. Furthermore, via interpolation, combinations of cost and fuel displacement at which ISCC becomes competitive in the electricity market can be deduced.

A range of reasonable values of uncertain ISCC performance parameters was ascertained from technological analyses of ISCC in the literature (Barigozzi et al. 2012; Spelling and Laumert 2015). Discrete values along each range were chosen for evaluation. The dimensions evaluated here are investment cost, policy definition, and fuel savings. All possible combinations of a set of discrete values for these parameters were evaluated. Once all possible combinations were evaluated in MARKAL, the optimized model results are analyzed to determine the extent to which ISCC is adopted by the model under the different assumptions.

In the representation of ISCC in MARKAL, most parameters (such as capacity factor and lifetime) are based on those of an advanced NGCC unit. NGCC units are assumed to have a base cost of approximately \$1000/kW and an efficiency of 55% [source (EIA 2015)]. Operation and maintenance (O&M) and investment costs for ISCC will be higher than for NGCC units, but demand for fuel will be lower. Emissions are modeled based on the amount of natural gas that is combusted per unit of electricity produced. As a result, this technology will have lower air pollutant and greenhouse gas emissions per kWh of electricity generated compared to electricity generated from the same size NGCC unit.

Ranges for the cost and fuel savings of ISCC to be analyzed were derived from values given in Barigozzi et al. (2012) and Spelling and Laumert (2015). Four different investment costs were considered, representing an additional \$700–1000/kW above an NGCC unit. Four different levels of fuel displacement, ranging from 15 to 30% lower fuel use than NGCC unit, are considered. The fixed O&M costs, which must be paid regardless of how much electricity generation occurs at a facility, are varied from \$9/kW to \$20/kW. The variable operating costs, which are based on generation, range from \$1.8/MWh to \$2.4/MWh. While these parameters, particularly fuel savings, may be optimistic since Barigozzi et al. studied a favorable location, early installations are likely to be in the most suitable sites. Increasing the size of the solar collector area would be one factor that could drive capital costs higher but would also increase fuel displacement. Thus, fuel displacement and capital cost are correlated in the real world. Here, it is assumed the energy collected and cost of the collector are uncertainties that are independent of one another.

Another parameter that may affect ISCC penetration is the role that ISCC plays in meeting an RPS. RPSs have been shown to be important factors for technology adoption (Chandel et al. 2012). As this hybrid technology is partly renewable and partly fossil fuel-based, it is unclear how state governments might determine compliance with an RPS. It is possible that only the fraction of electricity produced from ISCC via solar could be counted toward meeting a particular RPS, which is referred to here as a "partial" RPS qualification or "PR." However, another option could be to incentivize ISCC by allowing all of its output to be considered as renewable under an RPS, referred to as "full" RPS qualification or "FR." This latter option could also be the case if the natural gas were derived from landfill gas or other renewable sources. Both RPS accounting options are evaluated, and the option of not having ISCC count toward the RPS, a qualification of "none" or "NR." Therefore, each of the sixteen fuels and price combinations is modeled three times. These combinations are expressed in Table 1, and each combination is given a scenario name. The * is used as a wildcard to refer to a set of scenarios with similar characteristics, e.g., "FR-30%-*" would refer to all scenarios in the first line of Table 1.

An additional parameter was also explored: the price of natural gas. ISCC market penetration was evaluated for low and high natural gas price estimates that were derived from the AEO (EIA 2016). A subset of the scenarios in Table 1, indicated with a superscript t, "t", was also evaluated using alternative supply curves for natural gas, including: (1) a scenario in which natural gas is plentiful and therefore inexpensive (approximately half the base price), and (2) a scenario where natural gas has low availability and therefore high cost (approximately twice the base cost).

Results

MARKAL modeling suggests that ISCC would be able to achieve market penetration in the western US over a wide range of assumptions. This result is explored along several dimensions. First, total market penetration for each combination of assumptions is characterized and examined. This includes assumptions about the technology as well as different policy and fuel price eventualities. Next, the net impact on emissions is evaluated, taking into account which technologies are being displaced. Scenarios are sometimes grouped using wildcards (*) to highlight trends.

Market penetration

Electricity generated by ISCC in 2050 for each of the nested sensitivity model runs is presented in Fig. 3. The ISCC technology is projected to penetrate the electricity production market for most combinations of assumptions, producing as much as 14% of the national electricity in 2050. Regions 7, 8, and 9 produce as much as 40%, 26%, and 37% of their electricity from ISCC, respectively. Cost, fuel savings, and RPS classification were all observed to affect ISCC market share. The parameter with the greatest influence was RPS classification. If ISCC is not considered to be renewable (the NR-*-* scenarios), very optimistic cost and fuel displacement assumptions are required for a non-negligible ISCC market share. If ISCC is classified as fully compliant with the RPS (FR-*-*), market share is achieved for all combinations of cost and fuel savings. A counter-intuitive observation is that when ISCC partially satisfies the RPS (PR-*-*) the highest ISCC market penetrations are observed for

Table 1 Listing of scenarios that were evaluated

RPS	Fuel displaced (%)	Capital cost increase			
		$700/kW	$800/kW	$900/kW	$1000/kW
Full	30	FR-30%-$700[t]	FR-30%-$800	FR-30%-$900	FR-30%-$1 k
	25	FR-25%-$700	FR-25%-$800	FR-25%-$900	FR-25%-$1 k
	20	FR-20%-$700	FR-20%-$800[t]	FR-20%-$900	FR-20%-$1 k
	15	FR-15%-$700	FR-15%-$800	FR-15%-$900	FR-15%-$1 k
Partial	30	PR-30%-$700[t]	PR-30%-$800	PR-30%-$900	PR-30%-$1 k
	25	PR-25%-$700	PR-25%-$800	PR-25%-$900	PR-25%-$1 k
	20	PR-20%-$700	PR-20%-$800[t]	PR-20%-$900	BAU
	15	BAU	BAU	BAU	BAU
None	30	NR-30%-$700[t]	NR-30%-$800	BAU	BAU
	25	NR-25%-$700	BAU	BAU	BAU
	20	BAU	BAU	BAU	BAU
	15	BAU	BAU	BAU	BAU

Parameter combinations denoted by business as usual (BAU) are scenarios where the ISCC technology is not competitive and therefore the results mimic a BAU scenario

[t]Indicates cases that were also evaluated with high and low natural gas prices

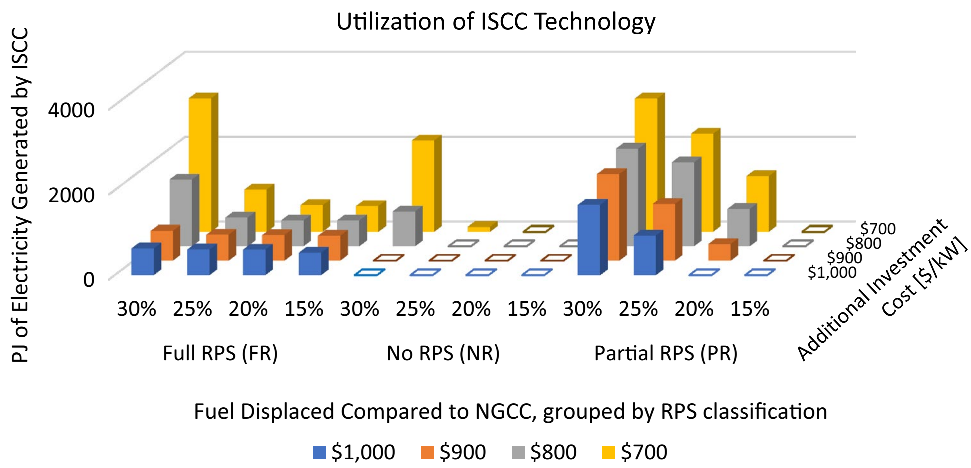


Fig. 3 The output of electricity in 2050 from ISCC when modeled under various possible cost, fuel reduction, and RPS scenarios. The outlined squares represent no generation

many of the cost-based combinations that were evaluated. The impact of partial RPS classification is examined later in this paper under "Impact of partial RPS" section.

Evaluating electricity generation technologies in individual regions helps inform how ISCC interacts within the suite of available technologies. The electricity generation mix for select scenarios in Regions 7–9 is displayed in Fig. 4, while the market penetration of ISCC for each scenario by region is presented in "Appendix". The BAU (i.e., a business as usual model run with on-the-book policies and a baseline technology trajectory that does not include ISCC), and three high ISCC market penetration scenarios are shown. These scenarios are chosen for this figure because it is easier to visualize market penetration and trade-offs in high penetration scenarios. In the NR-30%-$700 scenario, ISCC displaces natural gas generation compared to BAU in all regions. In the fully and partially RPS-classified version of this scenario (FR-30%-$700 and PR-30%-$700), there is also a reduction in natural gas and an increase in ISCC. However, Region 9 experiences a reduction in solar power, and waste-to-energy plants, which combust municipal solid waste (MSW), are completely displaced. The Region 9 RPS, which is the most stringent regional RPS representation, appears to be a major factor driving the use of ISCC. MSW is used in the BAU case to satisfy RPS requirements, but if a less expensive alternative is available, then RPS will drive use of that alternative.

In all scenarios, including BAU, Region 8 (Mountain) has more electricity production from coal than do Regions 7 and 9. Also, less ISCC is added in Region 8. When ISCC contributes toward the RPS in Region 8, it displaces a portion of the region's relatively high level of wind power. When the technology is sufficiently inexpensive, it also displaces some of the region's natural gas generation. When ISCC is considered to be only partially renewable (PR-*-*), Region 8 is the first to stop using it as costs increase. This response can be seen in supplemental Figs. 6, 7 and 8. In Region 7, ISCC tends to displace NGCC units since they fulfill a similar role in meeting base and shoulder loads. ISCC also displaces renewables if it provides a lower cost way to satisfy the RPS.

Impact of partial RPS

Market penetration behavior under the partial RPS classification behaved differently than expected a priori. In many of the PR-*-* scenarios, the total quantity of ISCC used is higher than in the other scenarios with the same cost and efficiency (e.g., FR-*-* or NR-*-*). In these PR-*-* scenarios, there is more ISCC generation in Region 9. As the cost increases and solar contribution declines (and therefore the RPS contribution declines), and when ISCC partially satisfies the RPS, the use of ISCC declines expeditiously in Region 8 compared to the fully renewable version. Most partial RPS scenarios also have comparatively less ISCC in Region 7.

In contrast, the electricity generated from ISCC in Region 9 *increases* compared to the full RPS scenario because more ISCC is required to offset the same amount of another fully qualifying renewable technology. Region 9 has the most stringent RPS requirement. When ISCC can partially satisfy the RPS, a smaller percent of a large amount of ISCC satisfies the RPS as opposed to a moderate amount of ISCC use that fully satisfies the requirement. The remaining fraction of the generation also supplies needed electricity. As costs increase, however, the technology becomes too expensive for the small portion it contributes to the RPS, and it is not used at all. Even with the increased use of the technology, ISCC satisfies less of the Region 9 RPS requirements in the PR-*-* scenarios than the FR-*-* scenarios.

Natural gas prices

Alternative assumptions about the trajectory of future natural gas prices were examined to determine whether they

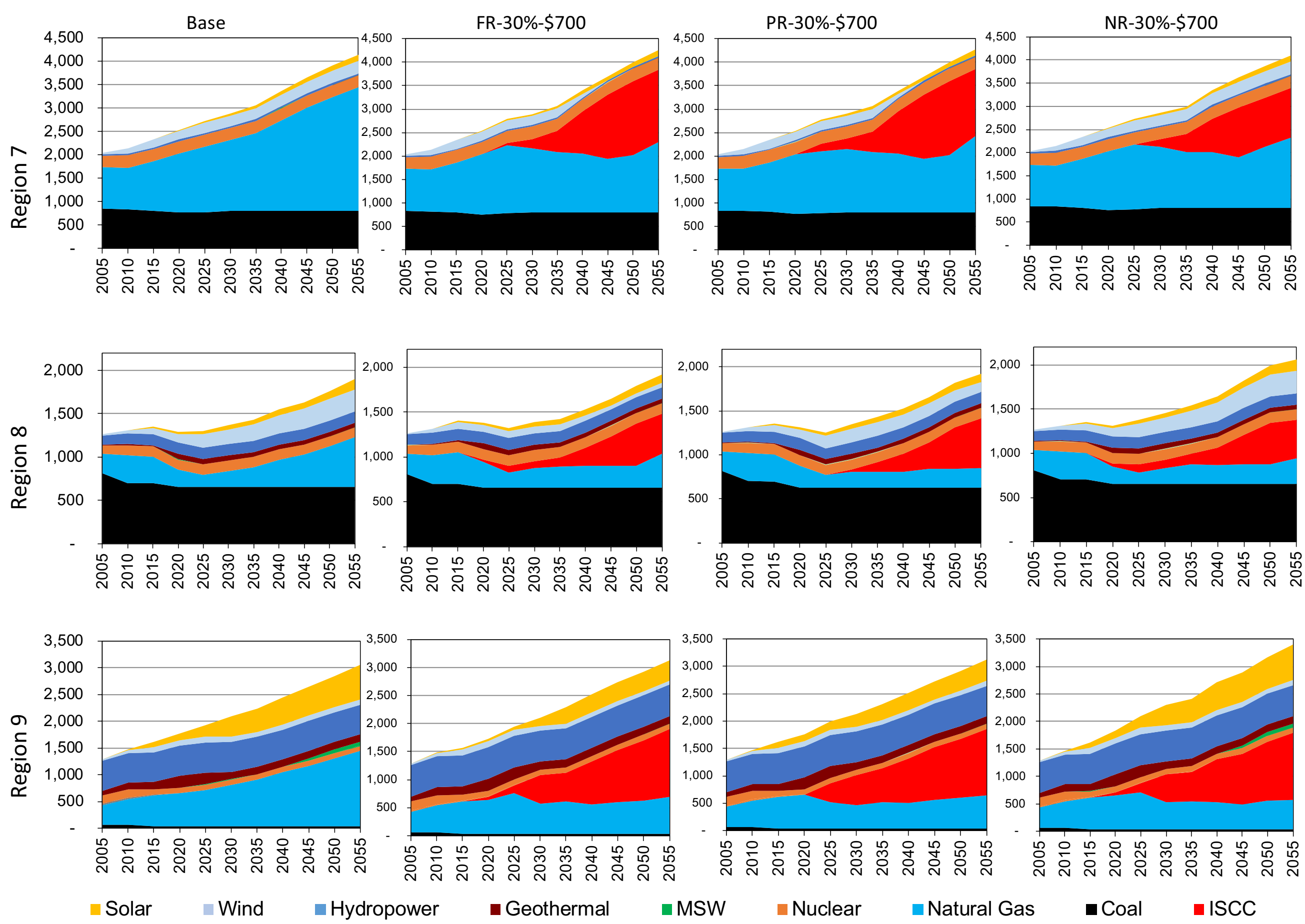


Fig. 4 Electricity generation (in PJ) by energy category in Regions 7, 8 and 9 in four different scenarios: the BAU without ISCC, and the scenarios where ISCC exists at its least expensive point for each level of RPS satisfaction (FR-30%-$700, PR-30%-$700, and NR-30%-$700). MSW stands for Municipal Solid Waste. Solar includes both concentrated solar power and photovoltaic generation, but not generation incorporated in ISCC

would influence the level of market penetration of ISCC. The three scenarios in which ISCC is most attractive (*-30%-$700) for each level of RPS classification are tested under high and low gas price assumptions. Also evaluated were two scenarios where ISCC is a bit more expensive and less efficient (FR-20%-$800 and PR-20%-$800). The resulting electricity production from ISCC for each of these model runs is presented in Fig. 5.

These results indicate an interesting interaction between natural gas prices and ISCC market penetration. This interaction occurs because the ISCC technology can help reduce natural gas use but also depends on natural gas. When ISCC is inexpensive and displaces a relatively large portion of the natural gas needed for NGCC, more ISCC is used as the price of natural gas increases. This response occurs because ISCC is providing a method to avoid paying the high fuel costs associated with pure natural gas generation. However, when natural gas is inexpensive and ISCC does not satisfy RPS, ISCC is not used at all because the solar equipment is more expensive than the fuel it would displace. Conversely, when ISCC displaces only 20% of the natural gas needed by a traditional NGCC unit, use of the technology decreases as natural gas prices increase. Because this technology still depends on natural gas to operate, the high cost of the fuel impacts the technology negatively. As in the scenarios with base natural gas price, the partial RPS classification of the technology may result in higher ISCC utilization because a larger amount of the technology is needed to meet the same RPS demands.

Emissions

Next, system-wide emission implications are evaluated. MARKAL provides this information by evaluating ISCC in the context of the full energy system, including not only the direct ISCC emissions, but also the displacement of emissions from competing technologies. Thus, the model estimates implications for emissions in other sectors as those

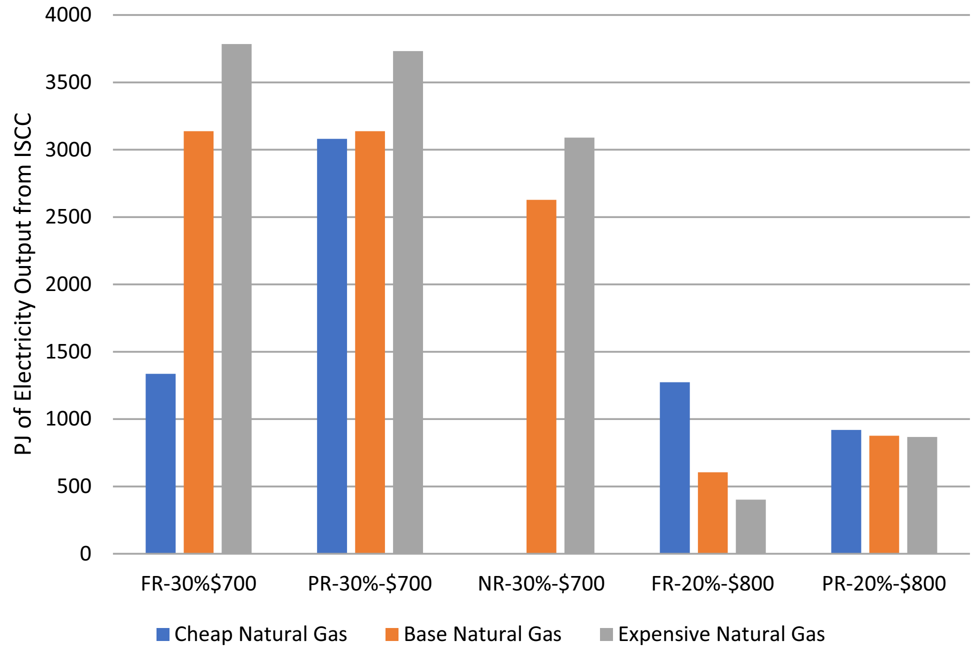


Fig. 5 Utilization of ISCC with relatively cheap and expensive natural gas in 2050

sectors respond to changes in fuel prices. Our results suggest that when ISCC is used to meet RPS goals, it is more likely to displace other renewable technologies, which can lead to a net increase in some emissions.

Emission implications vary by region as well as by scenario. Change in electric sector emissions in 2050, relative to BAU, is presented in Table 2. The EPAUS9r database also includes air emissions associated with extraction, processing, and distribution of fossil fuels, including oil, coal, and natural gas. Natural gas extraction, processing, and transmission are the primary sources of CH_4 emissions in the energy system. Natural gas is used within other sectors as well; therefore, extraction-related emissions have been multiplied by the fraction of natural gas used in the electric sector to allocate upstream emissions to electricity generation. This adjusted life cycle value is presented in Table 2.

In Region 7, the most optimistic scenarios (*-30%-$700) experience the largest emission benefit. In these scenarios, there are reductions in CO_2 and CH_4 for all RPS classifications, and NO_x reductions for NR-30%-$700. In other scenarios where ISCC is used in Region 7, there are increases in CO_2, NO_x and CH_4 emissions. Region 7 is rich in both fossil and renewable resources; therefore, as ISCC becomes more expensive, it is no longer used unless it fully classifies for RPS. When ISCC is used, ISCC displaces both NGCC and wind, resulting in a slight emissions benefit from reducing natural gas combustion. However, ISCC displaces most of the wind in this region, so that the combustion portion of generation produces more emissions than an entirely renewable form of generation.

In Region 8, many of the emissions changes are small on a percentage basis, partly because the high level of coal in this region dominates the emission totals, and partly because less ISCC is added than in other regions. CO_2 emissions increase in all FR-*-* scenarios since ISCC displaces wind. CO_2 increases up to 9% over BAU in 2050 and increases the most for fuel displacement of 25%. The directionality of change of CH_4 emissions is the same as for CO_2 because it is associated with the same shifts in the electricity mix. When ISCC fully classifies for RPS (FR-*-*) in Region 8, emissions of NO_x, PM, and VOC also increase. When ISCC does not fully classify for RPS (PR-*-* or NR-*-*), very little ISCC is used in Region 8, and the emission impact in this region therefore is small. There are reductions in CO_2 and CH_4 for the most efficient non-RPS scenarios (NR-30%-*) and reductions in NO_x, PM, and VOCs for the two most optimistic partial RPS scenarios (PR-30%-$700 and PR-30%-$800). Since ISCC displaces natural gas but not wind when not renewable in Region 8, there is a decrease in emissions; however, when it is also displacing emission-free wind, there is an increase in emissions.

Much larger percent changes in emissions occur in Region 9. CO_2 and CH_4 attributed to electricity generation increase for scenarios where the technology fully classifies for RPS but decreases for those scenarios where it does not. The FR-30%-$700 and FR-30%-$800 scenarios are exceptions, both experiencing a 1% decrease in CO_2. When ISCC partially classifies for RPS, CO_2 emissions decrease, but CH_4 emissions experience a slight increase. However, NO_x, SO_2, VOC, and PM (both coarse and fine) emissions are much lower in Region 9 for all scenarios where ISCC has full or partial RPS classification, and only very slightly lower or the same as the business as usual projection in the NR-*-* scenarios. One interesting result is that CH_4

Table 2 Emission changes by scenario, region, and pollutant presented as a percent change from a business as usual future in 2050

RPS	fuel displaced	Capital Cost Increase	Region 7							Region 8							Region 9						
			CO_2	NO_x	SO_2	PM_{10}	$PM_{2.5}$	VOC	CH_4	CO_2	NO_x	SO_2	PM_{10}	$PM_{2.5}$	VOC	CH_4	CO_2	NO_x	SO_2	PM_{10}	$PM_{2.5}$	VOC	CH_4
Full	30%	$700	-2	2	0	1	1	0	-3	5	1	0	0	0	0	13	-1	-55	-85	-96	-45	-75	5
		$800	5	2	0	0	0	0	6	7	2	0	0	0	0	17	-1	-54	-85	-96	-45	-75	6
		$900	5	2	0	0	0	0	6	8	4	0	2	2	2	18	11	-51	-85	-96	-44	-75	17
		$1,000	4	1	0	1	1	0	5	7	4	0	2	2	2	14	11	-51	-85	-96	-44	-75	16
	25%	$700	5	2	0	0	1	0	6	9	4	0	2	2	2	20	8	-52	-85	-96	-45	-75	12
		$800	5	1	0	0	0	0	6	8	4	0	2	2	2	18	12	-51	-85	-96	-44	-75	17
		$900	5	2	0	1	1	0	6	7	3	0	2	2	2	14	11	-51	-85	-96	-45	-75	16
		$1,000	5	2	0	1	0	0	6	6	4	0	2	2	2	13	9	-52	-85	-96	-45	-75	14
	20%	$700	5	1	0	0	1	0	6	7	4	0	2	2	2	15	12	-51	-85	-96	-45	-75	16
		$800	5	2	0	1	1	0	6	7	4	0	2	2	2	14	10	-52	-85	-96	-45	-75	15
		$900	5	2	0	1	0	0	6	7	4	0	2	2	2	14	10	-52	-85	-96	-45	-75	15
		$1,000	5	2	0	1	0	0	6	6	2	0	1	1	1	15	10	-51	-85	-96	-44	-74	15
	15%	$700	5	2	0	1	1	0	6	7	4	0	2	2	2	15	11	-51	-85	-96	-45	-75	15
		$800	5	1	0	1	0	0	6	7	3	0	2	2	2	15	11	-51	-85	-96	-44	-74	15
		$900	5	1	0	1	0	0	6	6	2	0	1	1	1	14	11	-51	-85	-96	-44	-74	15
		$1,000	5	2	0	0	0	0	6	4	1	0	0	0	0	12	10	-52	-85	-96	-44	-74	14
None	30%	$700	-7	-3	0	0	1	0	-9	-2	-1	0	0	0	0	-7	-15	-4	0	0	-1	0	-17
		$800	0	0	0	0	0	0	0	-1	0	0	0	0	0	-4	-14	-4	0	0	0	0	-15
	25%	$700	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-2	-1	0	0	0	0	-2
Partial	30%	$700	-2	7	0	0	1	1	-3	0	-5	0	-4	-4	-4	10	-3	-55	-85	-96	-45	-75	3
		$800	0	7	0	0	1	1	0	0	-3	0	-2	-2	-2	7	-3	-55	-85	-96	-45	-75	3
		$900	0	4	0	0	1	1	0	1	0	0	0	0	0	5	-4	-55	-85	-96	-45	-75	1
		$1,000	0	4	0	0	0	0	0	1	0	0	0	0	0	3	-4	-55	-85	-96	-44	-74	2
	25%	$700	0	4	0	1	1	1	0	1	0	0	0	0	0	4	-4	-55	-85	-96	-45	-74	1
		$800	0	4	0	0	1	0	0	1	0	0	0	0	0	3	-4	-55	-85	-96	-45	-74	2
		$900	0	3	0	-1	0	0	0	0	0	0	0	0	0	0	-5	-55	-85	-96	-44	-74	1
		$1,000	0	4	0	0	0	0	0	0	0	0	0	0	0	0	-5	-55	-85	-96	-44	-74	1
	20%	$700	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	-2	-22	-34	-39	-18	-30	1
		$800	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	-14	-22	-24	-11	-18	1
		$900	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Colors convey the same information as values but are added to help identify patterns. Darkest reds represent the largest increases and darkest blues represent the largest reductions

emissions decrease by up to 17% in NR-*-* scenarios but increase the same amount in FR-*-* scenarios and are within 3% of the BAU in PR-*-* scenarios. CH_4 emissions occur mostly in natural gas extraction. Thus, CH_4 emissions follow natural gas use. The large reductions in CO_2 and CH_4 in the NR-30%-$700 scenario are attributable to the decrease in natural gas generation compared to the BAU. In the renewable versions of this scenario (PR-30%-$700 and FR-30%-$700), there is also a reduction in solar power, which means that the slightly higher natural gas and ISCC contributions significantly decrease the CO_2 benefit and increase CH_4 emissions.

An unanticipated factor is the interplay among ISCC market penetration, RPS assumption, and the role of municipal solid waste (MSW), referred to as MSW in the graphics. The MSW category can include landfill gas combustion and waste-to-energy (WTE) facilities. In the runs where ISCC satisfies RPS, MSW is reduced or eliminated. The net NO_x, SO_2, PM, and VOC emissions in these runs are much lower than in the NR-*-* scenarios. While the MSW category in Fig. 4 includes both landfill gas and WTE, the latter dominates in Region 9.WTE has relatively high emissions compared to the very clean electricity mix of the Pacific Coast Region. Furthermore, MARKAL does not account for avoided CH_4 emissions from landfilling waste without capturing CH_4. The low system-wide emissions in Region 9 and relatively high emission rate of MSW lead to a large percent change in those emissions in the scenarios where use of that technology is not needed to satisfy RPS requirements. When ISCC is expensive and only partially satisfies the RPS, especially at the 20% level, it cannot displace all of the MSW and therefore has a smaller emissions benefit. MSW-related observations are affected by the assumed emission rates for MSW facilities. While these facilities use air pollution control devices, it is also possible that they may reduce emissions further through the use of additional emission controls, which would alter the net emission response to ISCC market penetration in relevant scenarios.

Natural gas prices affect emissions more than the differences between the ISCC utilization and through a larger variety of changes in the energy system. All of the scenarios with cheap natural gas have higher CH_4 emissions and lower emissions of local air pollutants compared with the scenarios with the base natural gas cost. The scenarios with expensive natural gas have lower CH_4 emissions, but slightly higher criteria air-pollutant emissions compared to the BAU scenario. The criteria pollutant emissions increase most in Region 7 but are within 8% of the BAU scenario. These changes are tied both to use of ISCC and to overall system changes associated with the price of natural gas. This example illustrates the interconnected nature of the energy system that allows MARKAL to provide additional insights beyond a typical LCOE analysis.

When natural gas is cheap, emissions tend to be higher than with base assumption natural gas or expensive natural gas. In these scenarios, ISCC is being used instead of renewable technologies rather than replacing other natural gas generation. The reduced cost of natural gas generation with inexpensive fuel means that ISCC provides little cost-benefit over standard NGCC units. In both scenarios where ISCC is assumed to fully satisfy RPS (FR), and natural gas is cheap, CO_2 is 42% higher and CH_4 is 29% higher in Region 9 than in the BAU scenario.

Discussion and conclusions

This paper assessed the conditions under which this hybrid concentrated solar and natural gas, namely ISCC, facility could be economically viable in the future electricity grid. Optimistic assumptions about capital costs and natural gas displacement increase the utilization of ISCC. Although all versions of the ISCC technology have a higher investment cost than NGCC units, the hybrid technology results in fuel savings and thus the lifecycle cost of the ISCC decreases.

The results are very sensitive to natural gas prices, which indicate that uncertainty in natural gas prices may factor heavily into decisions about whether to invest in this technology. The version of MARKAL used here has perfect foresight (e.g., it considers all time steps within a 50-year modeling period simultaneously), so while different cost projections were tested, the risk associated with unpredictable gas prices was not. While fuel prices directly impact adoption of ISCC, they also alter the rest of the energy mix, changing the system-wide emissions trends.

Selecting a site with adequate solar resources would be important in building an actual facility, as it will be a large factor in ensuring that the reduction in required natural gas is achieved. The area on which to build this facility is larger than the area required for many power plants, so additional analysis of space requirements and viable locations could be useful.

Classification of this technology in state RPS structures will change the contribution of this technology to electricity generation and the emissions generated by the overall electricity system, but there may be a trade-off for some emissions or the total amount of renewable generation. Deciding how ISCC might fit optimally into RPS will be an important topic of follow-up research. If all or a large percentage of the ISCC technology satisfies the RPS in Region 9 (along the Pacific coast), there would be improvements to local air quality stemming from reductions in electric sector criteria air pollutants, but there would be an increase in greenhouse gases. When the technology is used but does not satisfy the RPS, there are much smaller changes to criteria pollutant emissions, but the greenhouse gas emissions are reduced. This case is interesting since there would be a difference in whether the benefit was more local or global based on local policy. In the other regions in which ISCC was evaluated, the changes in local air pollutants are very small in all scenarios, but the results suggest that there may be benefits or disbenefits of using the technology with regard to greenhouse gas emissions. The results also indicate the importance of assumptions about the emission factors of technologies that are displaced by ISCC. For example, our assumptions about the emissions from WTE facilities had an influence on net emissions associated with ISCC market penetration.

Air quality in any region will also be impacted by emissions from non-electric sector sources. For instance, Region 9 could experience large fractional improvements in electricity-related emissions, but this region has a relatively clean electric grid and significant transportation sector emissions. In 2015, 73% of NO_x emissions and 54% of CO_2 emissions in the region were attributable to transportation. Due to projected efficiency improvements, transportation emissions in 2050 in the BAU are projected to be much lower as well, increasing the impact of electric sector changes. In 2050 in the BAU scenario, 27% of CO_2 emissions, 16% of NO_x, and 32% of SO_2 emissions in Region 9 originate in the electric sector.

Although impacts to the electricity generation mix and some air emissions have been considered, there are other possible consequences of this technology. New transmission capability might impact the environment, particularly if facilities are sited far from demand. Upstream impacts for the changing technologies might also lead to an environmental impact. For example, there may be additional cooling-related water use demands for this type of facility.

However, the combination of two generation methods may provide benefits compared to solar and natural gas generation technologies at separate facilities.

This technology can be economically feasible in some areas even without additional policy. Although local or national policies in the future could increase the viability of this efficient technology, the scenarios here include only existing policies that are already on the books. Thus, it is possible for ISCC technological development to reduce emissions without requiring any new policies.

The results of this analysis can be generalizable to a wider range of technologies. Although a specific ISCC configuration is referenced in this paper, it is only to ensure that plausible values are represented. A benefit to the methodology employed is that any ISCC configuration that achieves the same investment and O&M costs and generates a similar fraction of electricity without additional fuel would respond the same way in MARKAL. In fact, other possible technologies with similar cost and emission profiles would respond in the model in the same way. Therefore, other possible hybridization methods, or alternative methods of creating incredibly efficient natural gas combined cycle facilities would behave similarly in the US electricity generation profile. This research could also provide insights for other countries. Regional differences in adoption of the technology may be used to generate insights into adoption across other parts of the globe that have similar existing grid mixes and solar availability.

Appendix

This appendix includes regional detail on the utilization of the ISCC technology in 2050 under various performance assumptions.

As an optimization model, MARKAL often produces a "bright line" analysis that can highlight when a technology is most economically optimal, even if only slightly. In Region 7, the lowest cost version of ISCC is the least cost option, but it is very close in total cost to NGCC and wind, which is what used in the higher cost cases.

See Figs. 6, 7 and 8.

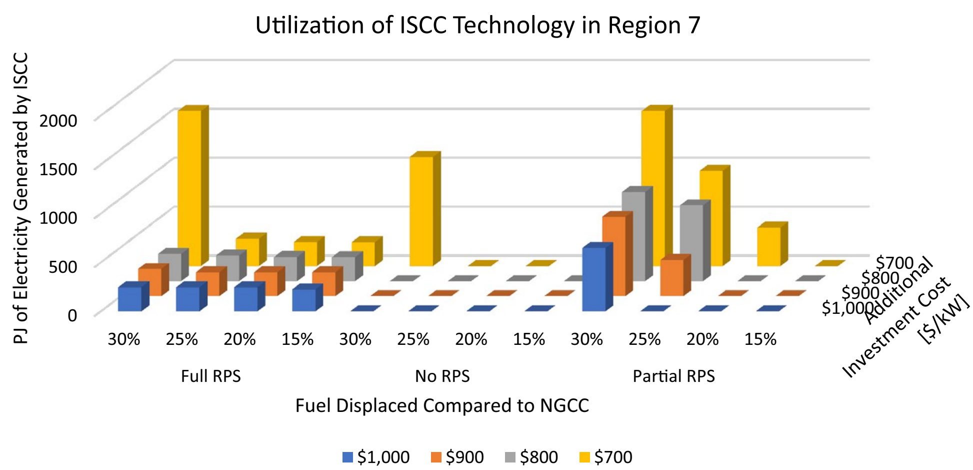


Fig. 6 2050 utilization of ISCC technology in Region 7

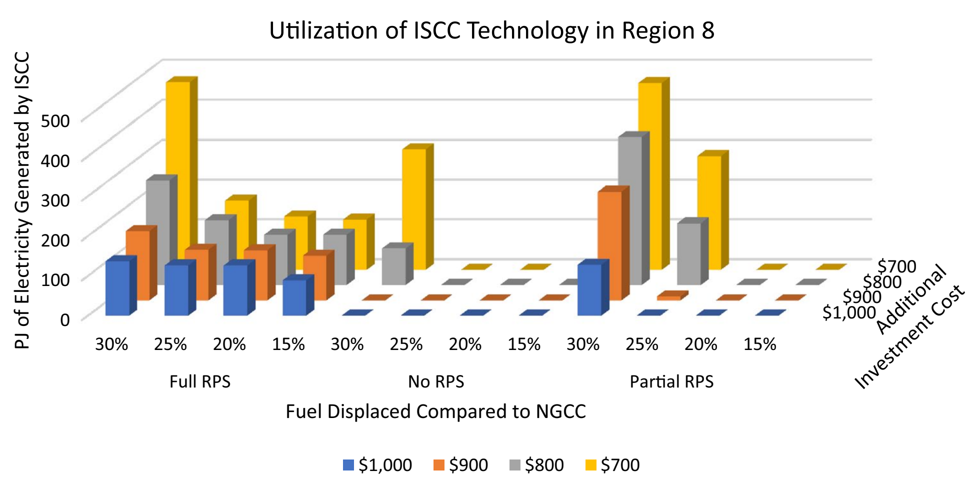


Fig. 7 2050 utilization of ISCC technology in Region 8

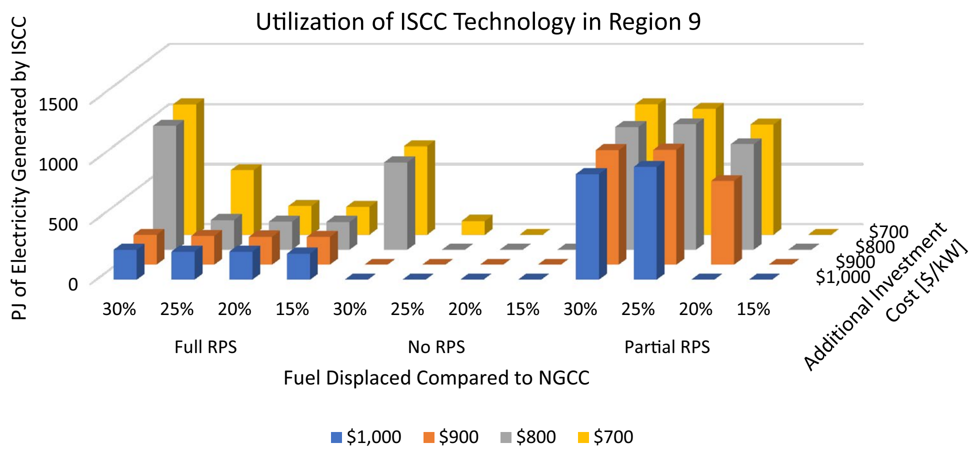


Fig. 8 2050 utilization of ISCC technology in Region 9

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