his way to frack and mine. His secretary of interior, for instance, opened up a huge swath of the Powder River Basin in Wyoming for coal extraction: The total basin contains some 67.5 gigatons worth of carbon (or more than 10 percent of the available atmospheric space). He's doing the same thing with Arctic and offshore drilling; in fact, as he explained on the stump in March, "You have my word that we will keep drilling everywhere we can... That's a commitment that I make." The next day, in a yard full of oil pipe in Cushing, Oklahoma, the president promised to work on wind and solar energy but, at the same time, to speed up fossil-fuel development: "Producing more oil and gas here at home has been, and will continue to be, a critical part of an all-of-the-above energy strategy." That is, he's committed to finding even more stock to add to the 2,795-gigaton inventory of unburned carbon.

Sometimes the irony is almost Borat-scale obvious: In early June, Secretary of State Hillary Clinton traveled on a Norwegian research trawler to see firsthand the growing damage from climate change. "Many of the predictions about warming in the Arctic are being surpassed by the actual data," she said, describing the sight as "sobering." But the discussions she traveled to Scandinavia to have with other foreign ministers were mostly about how to make sure Western nations get their share of the estimated $9 trillion in oil (that's more than 90 billion barrels, or 37 gigatons of carbon) that will become accessible as the Arctic ice melts. Last month, the Obama administration indicated that it would give Shell permission to start drilling in sections of the Arctic.

Almost every government with deposits of hydrocarbons straddles the same divide. Canada, for instance, is a liberal democracy renowned for its internationalism – no wonder, then, that it signed on to the Kyoto treaty, promising to cut its carbon emissions substantially by 2012. But the rising price of oil suddenly made the tar sands of Alberta economically attractive – and since, as NASA climatologist James Hansen pointed out in May, they contain as much as 240 gigatons of carbon (or almost half of the available space if we take the 565 limit seriously), that meant Canada's commitment to Kyoto was nonsense. In December, the Canadian government withdrew from the treaty before it faced fines for failing to meet its commitments.

The same kind of hypocrisy applies across the ideological board: In his speech to the Copenhagen conference, Venezuela's Hugo Chavez quoted Rosa Luxemburg, Jean-Jacques Rousseau and "Christ the Redeemer," insisting that "climate change is undoubtedly the most devastating environmental problem of this century." But the next spring, in the Simon Bolivar Hall of the state-run oil company, he signed an agreement with a consortium of international players to develop the vast Orinoco tar sands as "the most significant engine for a comprehensive development of the entire territory and Venezuelan population." The Orinoco deposits are larger than Alberta's – taken together, they'd fill up the whole available atmospheric space.

So: the paths we have tried to tackle global warming have so far produced only gradual, halting shifts. A rapid, transformative change would require building a movement, and movements require enemies. As John F. Kennedy put it, "The civil rights movement should thank God for Bull Connor. He's helped it as much as Abraham Lincoln." And enemies are what climate change has lacked.

But what all these climate numbers make painfully, usefully clear is that the planet does indeed have an enemy – one far more committed to action than governments or individuals. Given this hard math, we need to view the fossil-fuel industry in a new light. It has become a rogue industry, reckless like no other force on Earth. It is Public Enemy Number One to the survival of our planetary civilization. "Lots of companies do rotten things in the course of their business – pay terrible wages, make people work in sweatshops – and we pressure them to change those practices," says veteran anti-corporate leader Naomi Klein, who is at work on a book about the climate crisis. "But these numbers make clear that with the fossil-fuel industry, wrecking the planet is their business model. It's what they do."

According to the Carbon Tracker report, if Exxon burns its current reserves, it would use up more than seven percent of the available atmospheric space between us and the risk of two degrees. BP is just behind, followed by the Russian firm Gazprom, then Chevron, ConocoPhillips and Shell, each of which would fill between three and four percent. Taken together, just these six firms, of the 200 listed in the Carbon Tracker report, would use up more than a quarter of the remaining two-degree budget. Severstal, the Russian mining giant, leads the list of coal companies, followed by firms like BHP Billiton and Peabody. The numbers are simply staggering – this industry, and this industry alone, holds the power to change the physics and chemistry of our planet, and they're planning to use it.

They're clearly cognizant of global warming – they employ some of the world's best scientists, after all, and they're bidding on all those oil leases made possible by the staggering melt of Arctic ice. And yet they relentlessly search for more hydrocarbons – in early March, Exxon CEO Rex Tillerson told Wall Street analysts that the company plans to spend $37 billion a year through 2016 (about $100 million a day) searching for yet more oil and gas.

There's not a more reckless man on the planet than Tillerson. Late last month, on the same day the Colorado fires reached their height, he told a New York audience that global warming is real, but dismissed it as an "engineering problem" that has "engineering solutions." Such as? "Changes to weather patterns that move crop-production areas around -- we'll adapt to that." This in a week when Kentucky farmers were reporting that corn kernels were "aborting" in record heat, threatening a spike in global food prices. "The fear factor that people want to throw out there to say, 'We just have to stop this,' I do not accept," Tillerson said. Of course not – if he did accept it, he'd have to keep his reserves in the ground. Which would cost him money. It's not an engineering problem, in other words – it's a greed problem.

You could argue that this is simply in the nature of these companies – that having found a profitable vein, they're compelled to keep mining it, more like efficient automatons than people with free will. But as the Supreme Court has made clear, they are people of a sort. In fact, thanks to the size of its bankroll, the fossil-fuel industry has far more free will than the rest of us. These companies don't simply exist in a world whose hungers they fulfill – they help create the boundaries of that world.

Left to our own devices, citizens might decide to regulate carbon and stop short of the brink; according to a recent poll, nearly two-thirds of Americans would back an international agreement that cut carbon emissions 90 percent by 2050. But we aren't left to our own devices. The Koch brothers, for instance, have a combined wealth of $50 billion, meaning they trail only Bill Gates on the list of richest Americans. They've made most of their money in hydrocarbons, they know any system to regulate carbon would cut those profits, and they reportedly plan to lavish as much as $200 million on this year's elections. In 2009, for the first time, the U.S. Chamber of Commerce surpassed both the Republican and Democratic National Committees on political spending; the following year, more than 90 percent of the Chamber's cash went to GOP candidates, many of whom deny the existence of global warming. Not long ago, the Chamber even filed a brief with the EPA urging the agency not to regulate carbon – should the world's scientists turn out to be right and the planet heats up, the Chamber advised, "populations can acclimatize to warmer climates via a range of behavioral, physiological and technological adaptations." As radical goes, demanding that we change our physiology seems right up there.

Environmentalists, understandably, have been loath to make the fossil-fuel industry their enemy, respecting its political power and hoping instead to convince these giants that they should turn away from coal, oil and gas and transform themselves more broadly into "energy companies." Sometimes that strategy appeared to be working – emphasis on appeared. Around the turn of the century, for instance, BP made a brief attempt to restyle itself as "Beyond Petroleum," adapting a logo that looked like the sun and sticking solar panels on some of its gas stations. But its investments in alternative energy were never more than a tiny fraction of its budget for hydrocarbon exploration, and after a few years, many of those were wound down as new CEOs insisted on returning to the company's "core business." In December, BP finally closed its solar division. Shell shut down its solar and wind efforts in 2009. The five biggest oil companies have made more than $1 trillion in profits since the millennium – there's simply too much money to be made on oil and gas and coal to go chasing after zephyrs and sunbeams.

Much of that profit stems from a single historical accident: Alone among businesses, the fossil-fuel industry is allowed to dump its main waste, carbon dioxide, for free. Nobody else gets that break – if you own a restaurant, you have to pay someone to cart away your trash, since piling it in the street would breed rats. But the fossil-fuel industry is different, and for sound historical reasons: Until a quarter-century ago, almost no one knew that CO2 was dangerous. But now that we understand that carbon is heating the planet and acidifying the oceans, its price becomes the central issue.

If you put a price on carbon, through a direct tax or other methods, it would enlist markets in the fight against global warming. Once Exxon has to pay for the damage its carbon is doing to the atmosphere, the price of its products would rise. Consumers would get a strong signal to use less fossil fuel – every time they stopped at the pump, they'd be reminded that you don't need a semimilitary vehicle to go to the grocery store. The economic playing field would now be a level one for nonpolluting energy sources. And you could do it all without bankrupting citizens – a so-called "fee-and-dividend" scheme would put a hefty tax on coal and gas and oil, then simply divide up the proceeds, sending everyone in the country a check each month for their share of the added costs of carbon. By switching to cleaner energy sources, most people would actually come out ahead.

There's only one problem: Putting a price on carbon would reduce the profitability of the fossil-fuel industry. After all, the answer to the question "How high should the price of carbon be?" is "High enough to keep those carbon reserves that would take us past two degrees safely in the ground." The higher the price on carbon, the more of those reserves would be worthless. The fight, in the end, is about whether the industry will succeed in its fight to keep its special pollution break alive past the point of climate catastrophe, or whether, in the economists' parlance, we'll make them internalize those externalities.

It's not clear, of course, that the power of the fossil-fuel industry can be broken. The U.K. analysts who wrote the Carbon Tracker report and drew attention to these numbers had a relatively modest goal – they simply wanted to remind investors that climate change poses a very real risk to the stock prices of energy companies. Say something so big finally happens (a giant hurricane swamps Manhattan, a megadrought wipes out Midwest agriculture) that even the political power of the industry is inadequate to restrain legislators, who manage to regulate carbon. Suddenly those Chevron reserves would be a lot less valuable, and the stock would tank. Given that risk, the Carbon Tracker report warned investors to lessen their exposure, hedge it with some big plays in alternative energy.

"The regular process of economic evolution is that businesses are left with stranded assets all the time," says Nick Robins, who runs HSBC's Climate Change Centre. "Think of film cameras, or typewriters. The question is not whether this will happen. It will. Pension systems have been hit by the dot-com and credit crunch. They'll be hit by this." Still, it hasn't been easy to convince investors, who have shared in the oil industry's record profits. "The reason you get bubbles," sighs Leaton, "is that everyone thinks they're the best analyst – that they'll go to the edge of the cliff and then jump back when everyone else goes over."

So pure self-interest probably won't spark a transformative challenge to fossil fuel. But moral outrage just might – and that's the real meaning of this new math. It could, plausibly, give rise to a real movement.

Once, in recent corporate history, anger forced an industry to make basic changes. That was the campaign in the 1980s demanding divestment from companies doing business in South Africa. It rose first on college campuses and then spread to municipal and state governments; 155 campuses eventually divested, and by the end of the decade, more than 80 cities, 25 states and 19 counties had taken some form of binding economic action against companies connected to the apartheid regime. "The end of apartheid stands as one of the crowning accomplishments of the past century," as Archbishop Desmond Tutu put it, "but we would not have succeeded without the help of international pressure," especially from "the divestment movement of the 1980s."

The fossil-fuel industry is obviously a tougher opponent, and even if you could force the hand of particular companies, you'd still have to figure out a strategy for dealing with all the sovereign nations that, in effect, act as fossil-fuel companies. But the link for college students is even more obvious in this case. If their college's endowment portfolio has fossil-fuel stock, then their educations are being subsidized by investments that guarantee they won't have much of a planet on which to make use of their degree. (The same logic applies to the world's largest investors, pension funds, which are also theoretically interested in the future - that's when their members will "enjoy their retirement.") "Given the severity of the climate crisis, a comparable demand that our institutions dump stock from companies that are destroying the planet would not only be appropriate but effective," says Bob Massie, a former anti-apartheid activist who helped found the Investor Network on Climate Risk. "The message is simple: We have had enough. We must sever the ties with those who profit from climate change – now."

Movements rarely have predictable outcomes. But any campaign that weakens the fossil-fuel industry's political standing clearly increases the chances of retiring its special breaks. Consider President Obama's signal achievement in the climate fight, the large increase he won in mileage requirements for cars. Scientists, environmentalists and engineers had advocated such policies for decades, but until Detroit came under severe financial pressure, it was politically powerful enough to fend them off. If people come to understand the cold, mathematical truth -- that the fossil-fuel industry is systematically undermining the planet's physical systems -- it might weaken it enough to matter politically. Exxon and their ilk might drop their opposition to a fee-and-dividend solution; they might even decide to become true energy companies, this time for real.

Even if such a campaign is possible, however, we may have waited too long to start it. To make a real difference – to keep us under a temperature increase of two degrees – you'd need to change carbon pricing in Washington, and then use that victory to leverage similar shifts around the world. At this point, what happens in the U.S. is most important for how it will influence China and India, where emissions are growing fastest. (In early June, researchers concluded that China has probably under-reported its emissions by up to 20 percent.) The three numbers I've described are daunting – they may define an essentially impossible future. But at least they provide intellectual clarity about the greatest challenge humans have ever faced. We know how much we can burn, and we know who's planning to burn more. Climate change operates on a geological scale and time frame, but it's not an impersonal force of nature; the more carefully you do the math, the more thoroughly you realize that this is, at bottom, a moral issue; we have met the enemy and they is Shell.

Meanwhile the tide of numbers continues. The week after the Rio conference limped to its conclusion, Arctic sea ice hit the lowest level ever recorded for that date. Last month, on a single weekend, Tropical Storm Debby dumped more than 20 inches of rain on Florida – the earliest the season's fourth-named cyclone has ever arrived. At the same time, the largest fire in New Mexico history burned on, and the most destructive fire in Colorado's annals claimed 346 homes in Colorado Springs – breaking a record set the week before in Fort Collins. This month, scientists issued a new study concluding that global warming has dramatically increased the likelihood of severe heat and drought - days after a heat wave across the Plains and Midwest broke records that had stood since the Dust Bowl, threatening this year's harvest. You want a big number? In the course of this month, a quadrillion kernels of corn need to pollinate across the grain belt, something they can't do if temperatures remain off the charts. Just like us, our crops are adapted to the Holocene, the 11,000-year period of climatic stability we're now leaving... in the dust.

This story is from the August 2nd, 2012 issue of Rolling Stone.

Related
Bill McKibben: The Arctic Ice Crisis
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Climate Change and the End of Australia

http://www.rollingstone.com/politics/news/global-warmings-terrifying-new-math-20120719

I have a new Great-granddaughter, her name is Madison, I ask myself what her 30th birthday present will be. Will it be an inhospitable climate where food shortages are the norm? She and all the Madisons are the reason I speak to you today.

The world's leading scientists are advising us that by the 2047 we will have passed the tipping point of creating irreparable harm to the environment that sustains all life.

Yesterday's Seattle Times had a picture and article depicting the air pollution, caused by burning our coal, in China. A few weeks ago they had a series of articles describing the acidification of the waters on our coasts and the destruction of the shellfish industry as a result. These are not things that might happen or will happen they are the now.

The shadows we have created will continue to chase us and we can chose to ignore them, saying WHAT SHADOWS, but they are real and they are now. Old habits die hard, fear of change or sacrifice will continue to hounds us, but we must stop our self-abusive behavior and chose a path which puts our children and grandchildren, down to the 7th generation, first.

In our humanness we only grow or change when challenged by the pain of our creation. It may seem like a great effort to try a new way of life, but unless we do we will surrender life as we know it.

We select picture we want tattooed. In life, it is we who select what we will become by the actions we perform. There is no reason to go through life thoughtlessly, letting accident and the need for more to shape us. It is like allowing oneself to be tattooed by a blind man. How can you help but turn out old and ugly. Whether we emerge beautiful or ugly is our sole responsibility.

We can not reverse the damage (cancer) we have created in our ignorance and drive to create more wealth, but we can put it in a state of remission. Just like the recovering alcoholic/addict the path is not easy not is it without challenge and sacrifice but we must chose it or we perish.

In conclusion I would offer that there is not just one large saving path to healing, but many small ones. A leadership role in refusing to allow more coal to be shipped from our ports, enacting a well reasoned carbon tax, a progressive transportation system and making this issue part of the education of our children are only a few of those paths.

Madison and I thank you for providing a Happy 30th Birthday Present.

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ENVIRONMENTAL ENTREPRENEURS
www.e2.org

October 23, 2013

Climate Legislative and Executive Workgroup
Public Hearing #2
Seattle, WA

Honorable Members of the Climate Legislative and Executive Workgroup,

The Pacific Northwest Chapter of Environmental Entrepreneurs (E2) is pleased to have the opportunity to testify before the Climate Legislative and Executive Workgroup. E2 is a non-partisan national organization of business leaders who promote sound environmental policy that builds economic prosperity. Founded in 2000, E2's network of more than 850 members have built, financed or otherwise worked to develop more than 1400 companies that have created more than 500,000 jobs nationwide. E2's members manage over $108 billion in venture and private equity capital that will flow into new companies.

E2 representatives testifying at CLEW Hearing #2 include:

- Jeremy Stone, VP of Clean Power Research and E2 member
- Eric Berman, investor and Board member of Northwest Energy Angels and E2 member
- Elizabeth Bekiroglu, corporate attorney and a chapter director of E2's PNW Chapter

Our written testimony is attached.

Thank you very much for your consideration and leadership.

Sincerely,

Jeremy Stone
Eric Berman
Elizabeth Bekiroglu

October 23, 2013

Members of the Climate Legislative Executive Workgroup,

My name is Jeremy Stone. I am Vice President of Clean Power Research, a software company in the clean technology sector that employs 15 people here in Washington. I am also a member of Environmental Entrepreneurs (E2), a national non-partisan community of business leaders who provide a business voice for the environment. Founded in 2000, E2's network of more than 850 members has built, financed, or otherwise worked to develop more than 1,400 companies that have created more than 500,000 jobs nationwide.

You'll sometimes hear the argument that it costs too much to solve the climate crisis. I'm here to tell you that we can solve the climate crisis using free markets and continue to have a vibrant economy.

Everyone responds to price signals; people do and companies do. However, our market currently doesn't put a price on the effects of carbon emissions. Using fossil fuels seems cheap, although in fact it has very expensive consequences. We will continue to burn fossil fuels as long as they seem cheap.

Carbon pricing lets you put a price on carbon and return that revenue to the economy somewhere else. You can use the proceeds from carbon to reduce income tax, sales tax, payroll tax, B&O tax or whatever you like. You can also use it to help offset any regressive effects.

Carbon pricing can actually improve our economy by reducing other taxes. We should tax what we burn, not what we earn.

In 2008 British Columbia instituted a revenue-neutral carbon tax; since then, BC's economy has outperformed the rest of Canada's, and their emissions went down.

In 2012, the US suffered eleven weather events each costing more than $1 billion[1], with the cost of Superstorm Sandy alone expected to exceed $60 billion and the drought which afflicted half the country costing $11 billion. Indeed, a recent study from Munich Re, the world's largest reinsurer, found that over the last 30 years weather-related loss events in North America have quintupled, growing at a faster rate than anywhere else in the world.[2]

While the costs of climate change keep rising, so does the value of unleashing Washington state innovation and entrepreneurship to solve this problem. The expanding clean energy sector is a powerful platform to restore a robust economy and create millions of new jobs in every sector, from manufacturing to farming. Even during the last years of recession and without a market signal on carbon pollution, the renewable energy and energy efficiency sectors have grown at record rates.

It is a false choice to think that we need to choose between prosperity and solving the climate crisis. If we do not solve the climate crisis then we have no prosperity. It makes no business sense to do things that seem cheap in the near term but transform our farmland into desert, threaten our food and water security, and alter our world outside the bounds to which all life on Earth is adapted. We don't need to sacrifice our economy to solve the climate crisis; we need to de-carbonize our economy and build a clean energy future.

Thank you.

Jeremy Stone
Vice President of Clean Power Research
Environmental Entrepreneurs (E2)

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1 "Preliminary Info on 2012 U.S. Billion-Dollar Extreme Weather/Climate Events", National Climatic Data Center, December 2012.

2 Kuczinski, Tony, "Severe Weather in North America", Munich Re, October 2012.

E2

ENVIRONMENTAL ENTREPRENEURS

www.e2.org

October 23, 2013

Members of the Climate Legislative Executive Workgroup,

My name is Eric Berman. I am an electrical engineer and physicist by training, a software engineer by profession, and currently an investor and board member with Northwest Energy Angels (NWEA), an early-stage investing group that focuses on the CleanTech sector. I am also a member of Environmental Entrepreneurs (E2), because I believe strongly that the often-portrayed conflict between economic growth and the environment is a false one. Indeed, I believe that the opposite is true: sustainability is critical for a business to be successful, whether it is the explicit focus of the business (such as the companies in which I invest), or simply how a business operates.

We at NWEA see approximately 30 companies a year, almost all of them from the greater northwest region. They see large business opportunities in clean technologies. Our investments have totaled more than $12M, spread across 41 different companies, in fields ranging from clean water to waste mitigation to renewable energy generation and smart grid development. This is a vibrant sector, with tremendous innovation being driven by passionate entrepreneurs and significant opportunities for export.

The single biggest challenge our portfolio companies typically face is incumbency: the existing way that things are done (fossil fuels in particular) have long since amortized the bulk of the up-front capital costs (think pipelines, refineries, and power plants), have achieved economies of scale, and have benefited from years of implicit and explicit subsidies. All of these significantly raise barriers to entry by new entrants. Our goal for government is not to pick new industries, but to level the playing field. Markets work very well, but they are not good at pricing "externalities" such as environmental sustainability. Specifically, we need policies which internalize these costs. Finding a way to put a price on carbon is probably the most leveraged single step we could take to address this.

Climate change is a global problem and will require solutions from around the globe. By ensuring Washington leadership on climate and clean energy policy, the innovations we develop domestically will also be the products and services we export to the expanding international market for clean energy. Washington-based businesses can become leading suppliers of clean energy and other sustainability solutions. But it goes further than simply businesses that are explicitly in the cleantech sector: by adopting smart energy and carbon policies, all Washington businesses will become more globally competitive by reducing their resource intensity. Our region is already a model for the rest of the world, but we can do much more.

I have had the honor of being a member of two trade delegations from Seattle over the past few years, one to China and one to Scandinavia, to learn about what each of these regions is doing in the cleantech sector. In both places, we have met with government officials, analysts, entrepreneurs, and investors. What we saw were two wildly divergent political systems (communist/authoritarian in China, social democracy in Scandinavia) with very different environmental situations (China is an environmental catastrophe, whereas the water temperature is the only thing that would deter you from jumping into the water in Copenhagen), yet in both places governments (in their very different ways) are making sustainability a priority and are crafting policies to incentivize and reward industry for moving in the right direction. From China's State Grid corporation, the largest grid operator in the world, which is integrating vast new sources of wind energy, to offshore wind farms in resource-poor Denmark, to Chromogenics, a startup in Stockholm which is trying to build a more energy efficient window, each of these countries is responding to a consumer demand for sustainable solutions and smart government policies.

But perhaps the most striking thing to me from these trips was when we saw nearly identical data for both Denmark and Sweden that showed each country's GDP nearly doubling since 1990 (up 80% in Denmark), while energy use during the same period was basically flat and CO2 emissions fell approximately 25%. This I think is strong evidence that we can simultaneously achieve economic growth, sustainability, and CO2 reductions.

Thank you.

Eric Berman
Northwest Energy Angels (NWEA)
Environmental Entrepreneurs (E2)

October 23, 2013

Climate Legislative and Executive Workgroup
Public Hearing #2
Seattle, Washington

Members of the Climate Legislative and Executive Workgroup,

My name is Elizabeth Bekiroglu; I'm a corporate and securities law attorney and serve as in-house counsel to a Seattle-based Nasdaq-listed company. I'm here today as a Chapter Director of the Pacific Northwest Chapter of Environmental Entrepreneurs (E2). E2 is a non-partisan national organization of business leaders who promote sound environmental policy that builds economic prosperity. Founded in 2000, E2's network of more than 850 members has built, financed, or otherwise worked to develop more than 1,400 companies that have created more than 500,000 jobs nationwide. E2 members manage over $108 billion in venture and private equity capital that will flow into new companies.

The Pacific Northwest chapter of E2 strongly supports the implementation of a Clean Fuels Program in Washington. Washington already leads the nation with renewable jet fuel development and now has a critical opportunity to build on that leadership with a Clean Fuels Program.

Clean fuels are renewable, liquid transportation fuels that can replace traditional gasoline and diesel with less than half the greenhouse gas emissions. There will be a long-term requirement for liquid fuels for industrial, shipping and aviation. These long-term needs must be addressed by encouraging the development of sustainable, domestic fuels.

A clean fuels program is a market-based program that enables private industry to determine the most efficient way to domesticate our fuel supply. Clean fuel standards including those in California and British Columbia have helped to move advanced biofuels from a demonstration into a commercialization phase. E2's 2013 report on the clean fuels industry documents extensive economic activity surrounding clean fuels. 160 commercial scale facilities are currently planned, under construction or complete. Private investment in the advanced biofuel industry totals over $4.85 billion since 2007.

In California and British Columbia, existing and new facilities have sufficient capacity not only to meet but to exceed the fuel standards currently in effect. More fuels have entered the market, greenhouse gas emissions are being reduced, and there is a strong credit price. Credit prices today are above $70/ton. That $70/ton gives a healthy return to alternative fuel providers – about 60 cents for a gallon of advanced biofuel – but once blended, **costs have less than one penny of impact on the final price. That fraction of a penny today promotes a more renewable, diverse and domestic fuel supply, which can help us take control of our fuel imports and price volatility. This is the key to reducing negative impacts of the price instability of conventional fuels on our economy and on working families.**

We can accelerate the path to this outcome through a coordinated regional approach. Disconnected, standalone efforts by one state and one province are no match for the market signal of a linked, multistate program, especially if Washington leads the west coast on a path to coordinated fuel and electric vehicle programs. We suggest using the Pacific Coast Collaborative as the conduit for this regional collaboration. If Washington leads the PCC efforts, we can ensure that the Clean Fuels Program becomes a regional initiative that is more efficient and better harmonized, thereby encouraging other states to follow our example.

Thank you for your efforts to steer Washington and our nation along a path to a cleaner future and stronger economy.

Elizabeth Bekiroglu
Chapter Director, Pacific Northwest Chapter
Environmental Entrepreneurs (E2)

Harry Bell

Testimony for the 10.19.13 CLEW Public Hearing in Seattle

Good Evening.

I am Harry Bell and here representing the Washington State Chapter of the Society of American Foresters (www.forestry.org).

SAF is a national professional organization. Our mission is the scientific management of forest land to provide "Thriving Forests, Essential Resources and Healthy Communities." **We endeavor to provide the greatest good to the greatest number in the long run.**

Regarding climate change we have two areas of interest. The first is the effects of climate change on forests which I will not discuss tonight but you can find more about in our Journal of Forestry publication. The other is the effects of forest land management and specifically timber harvest on atmospheric carbon releases.

Using wood from working forests as a building material provides long term storage of carbon that is directly taken out of the atmosphere. The manufacture of alternative building materials, particularly steel and concrete, require large amounts of energy typically from fossil fuels or hydro power that could otherwise replace fossil fuels.

I live in a house built in 1929 during the heyday of old growth timber harvest. About half the weight of the wood in my house is captured atmospheric carbon. Those acres that were cut over have since grown into what we refer to as natural second growth. These have again been harvested, and most of that captured carbon is again stored in buildings. Today, those acres are again capturing atmospheric carbon that can be stored in buildings.

Compare this to the use of concrete or steel, both of which require energy to manufacture there by provide for enormous amounts of atmospheric release.

Comments Regarding Specific Action to Reduce Greenhouse Gas Emissions:

Adopt the WSSAF characterization of Working Forests that requires a balance of ecological, social and economic values and products.

Adopt a position of No-Net-Loss of these working forests.

Recognize that private forest land owners, who own about half of forest land in Washington, are being pushed by regulation and pulled by residential demand into forest land conversion.

Reward forest landowners for maintaining working forests that provide the ecological benefits of clean air, clean water, fish, wildlife, watershed health and biological diversity that they now provide without compensation.

In addition to the US Green Building Council's LEEDS program, adopt the Green Globe certified building (www.greenglobe.com) that explicitly emphasizes entire life cycle assessment of building materials and their manufacture impact on global warming.

Adopt the use of all three sustainable forest management certification systems. These are the American Tree Farm System, the Sustainable Forestry Initiative and the Forest Stewardship Council systems.

Use the building materials analyses, developed by The Consortium for Research on Renewable Industrial Materials (www.corrim.org), as a basis for policies that address the energy use and atmospheric emissions of building materials.

Handouts: CORRIM Fact Sheets 5 & 6

WSSAF Working Forest Position Statement

Harry Bell

Maximizing Forest Contributions to Carbon Mitigation

Science-based carbon strategies by CORRIM: a 15-research institution consortium (www.corrim.org).

Measuring all carbon pools is required:

- Carbon sink and source (pools) include all the renewable fibers supported by photosynthesis, and all the emissions from using hydrocarbons, with each being impacted by manufacturing processes.
- Life-cycle analysis provides a science-based method to understand how every stage of processing impacts the products we produce and the environmental burdens created or mitigated.
- Tracking carbon from cradle to grave, not just measuring one pool at a time, is essential to ensure that policies achieve their objectives and avoid counterproductive activities.

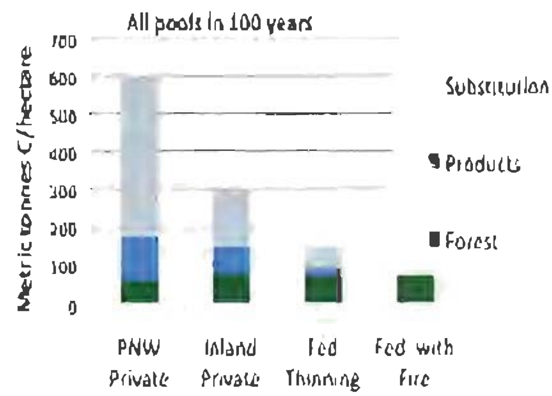
Getting the most carbon out of the atmosphere:

- Growing trees takes carbon out of the atmosphere storing it first in the forest. Harvesting trees stores the carbon in products, which displace the use of fossil-intensive products like steel and concrete.
- At the end of product life, wood can be recycled for a second life, burned as a fuel displacing fossil intensive fuels, or land-filled, extending carbon storage for many additional decades.
- When wood products or biofuels displace fossil-intensive products or fuels, a permanent reduction in fossil carbon emissions occurs. This is equally as important to mitigating climate change as storing carbon from the atmosphere in the forest.

The best among management options:

- Non-managed forests as they mature remove atmospheric carbon until mortality offsets growth, producing a storage pool that is no longer removing atmospheric carbon.
- Harvesting forests moves the carbon to other uses including fuels that displace fossil emissions and products that extend the forest carbon to new pools while displacing fossil- intensive materials like steel, brick, concrete, aluminum and plastic.
- ***The maximum carbon mitigation benefit results from using the forest as a carbon pump to store carbon in useful products that also displace fossil-intensive substitutes.***

Regional Carbon Comparisons



Incentives: Productive or Counterproductive? (Lippke and Perez-Garcia 2008):

- Current carbon exchanges that pay forest owners to defer or avoid harvesting for the increased forest carbon they store *are counterproductive*. Reducing wood uses results in increased use of fossil intensive products and emissions.
- Incentives to grow the forest faster through more intensive management and harvesting *will maximize the carbon across all pools*.
- Incentives to remove forest residuals to increase biofuels *can be productive; but not if the incentive diverts wood from higher valued uses* like fiberboards that substitute for fossil intensive products.
- Incentives for thinning high fire risk stands will *reduce the cost of and carbon emissions from fires* while also increasing the carbon stored in products and their displacement of fossil intensive products.
- Incentives that encourage builders to use life-cycle assessment in design and product selection, will mitigate carbon directly through their choices and bid the savings back, expanding the carbon mitigating resource supply chain. ***Given the high leverage from substitution, builders have the greatest opportunity to reduce emissions.***

Contacts: For more information and summary Fact Sheet #5 visit the CORRIM website at www.corrim.org or contact Bruce Lippke, University of Washington

Harry Bell

Washington State SOCIETY OF AMERICAN FORESTERS
4033 SW Canyon Road • Portland, OR 97221 • 503.224.8046

CHAPTERS: Central Washington • Mid-Columbia • North Olympic • North Puget Sound • South Puget Sound • Southwest Washington • Longview • Admiralty Inlet Chapter • Grays Harbor Student Chapter Green River Community College • University of Washington Student Chapter • Evergreen Student Chapter

WSSAF Working Forest Position Statement

Position

The Washington State Society of American Foresters (WSSAF) supports "No-Net-Loss" of working forests by encouraging the creation, restoration, protection, and enhancement of working forests in the State of Washington.

Characteristics of Working Forests

- A working forest must be an actively managed sustainable forest as measured in ecological, economic, and social terms. This implies a host of things—including the notion of permanence over time.
- A working forest must include a management plan that identifies objectives that will provide a balance of social, ecologic, and economic products and values and a schedule for management activities that will accomplish them.
- Active management on working forests means that silvicultural practices—including determination of tree species composition, stocking control, thinning, prescribed burning, and timber harvest—are planned and implemented recurrently and perpetually over most of the forestland area, causing a different balance of benefits than would occur naturally.
- A working forest must maintain the intrinsic value of the land. These values may include; soil productivity, historical or cultural resources, or other ecological or conservation values.

Issue

With increasing public awareness of the benefits of working forests as a desirable alternative to land-use change and development, it is timely for the Washington State Society of American Foresters to clarify what we mean by promoting working forests. In order to develop durable policies that support and maintain working forests, a common vision is necessary.

Discussion

Working forests may be small or large and can include single (stand scale) or multiple ownerships (landscape scale). **The operative factor is the existence of an over-all plan that characterizes the intent to produce multiple products and values across the entire forest.** In order to provide specific ecological benefits, some areas of a working forest may not receive silvicultural treatments or have planned timber harvest. Examples on a stand or stream reach scale are riparian stream buffers, un-harvested areas on unstable landforms, endangered species critical habitat, and non-forested wetlands. Examples on a landscape scale are wilderness areas and endangered species habitats as subsets of a larger working forests. Rarely can any single acre of forest provide all the goods and services we expect and need, but they are achievable with active management across the broader mosaic of a working forest landscape.

Working forests are managed forests, but not all managed forests are working forests. For example, a forest that is designated as a wilderness, and that is not a subset of a larger actively managed area, is not a working forest. Likewise, a forest that is managed solely for watershed protection, without the potential provision for periodic harvest of commercial timber products, is a managed forest but not a working forest. In general, working forests provide multiple benefits rather than single or exclusive benefits.

Conversion of Working Forests to Non-Working Forest Use

The area of working forest is decreasing on federal, state, corporate, and private forestland ownerships in Washington State. [a]

Federal lands continue to experience conversion from multiple to single use through administrative policy or legislative changes. **For example, the Adaptive Management Areas and Late Successional Reserves under the Northwest Forest plan are not working forests without similar acreages of Matrix Forest.** Also, forests managed under a Collaborative Forest Landscape Restoration Program, National Parks and Wilderness areas are not working forests if they do not plan for recurrent and perpetual timber harvest over most of the plan area. Without an equitable balance of objectives, including commodity production, these lands no longer support working forests.

Loss of federal working forests has had the unintended consequences of exacerbating forest health and fire risk across the landscape. Additionally, the lack of management and subsequent reduction of the commercial timber products has had a trickledown effect on rural communities ultimately resulting in mill closures. Fewer mills result in the lack of markets for periodic timber harvest that lower the value of commercial products from both public and private working forests and encourage conversion to non-forest land uses. Similarly, for 1989 through 2011 the Washington State Trust Land Transfer program has transferred 108,043 acres of working forest into recreational or ecological uses. [b] As such, they are no longer working forests.

For private commercial forest lands vertically integrated corporations, driven by federal tax policies, have sold large tracts of working forests to individual private investors and investment funds. Typically, to maximize returns and help finance these transactions, new investors "spin off" parcels for conversion into conservation areas, residential subdivisions, or commercial development.

As would be expected with a rising population, lands that were once productive working forests have increasing conservation or development value. As urban and suburban areas expand, it becomes increasingly difficult to continue to manage the remaining working forests. Local, state, and federal regulations have created disincentives for private forest landownership. **As property values and regulations increase, private forest landowners have sold lands to owners that choose not to manage them as working forests.** [a] In Western Washington non-National Forest timberland acres diminished at an average rate 30,000 acres per year from 1978 to 2001. [c] In Eastern Washington the average annual rate of conversion was 23,000 for years 1980 to 2002

This trend is especially evident with family and individual forest landowners that own approximately half of the private forestland in Washington. In addition to being in close proximity to areas with higher development values, these owners are disproportionately older than the general population and less willing to bear the burden of complex and costly regulations. [a] The sale of part or all of a tree farm can be an attractive financial alternative to the regulatory and market risks of managing a working forest when a landowner is faced with the need for retirement income or intergenerational transfer. Additionally, estate taxes frequently cause the sale of working forest land for non-forest uses.

Measures to Achieve No-Net-Loss of Working Forests

WSSAF supports the use of a variety of measures by federal, state, and local governments, landowners, and individual citizens that can help achieve no-net-loss working forests in Washington including:

- Land use policies that recognize the multiple values of working forests and respect the rights and responsibilities of private and public forest landowners.
- Public funding and support for enforcing existing forest practices laws and regulations.
- Promote the use of alternative best management practices that address site specific conditions rather than one size fits all regulations.
- Adequate funding for sufficient and peer reviewed research that is not influenced with policy preferences, [d] upon which to base good forest policy and adaptive management.
- Expanded markets by promoting the use of wood for construction and energy.
- Develop markets for ecological services that improve timber and non-timber resource economics.
- Education programs that emphasize recognition that wood is a renewable natural resource.
- Public and institutional education programs that promote the benefits of working forests.
- Provide credit to working forest landowners for their current and additional capture of atmospheric carbon, storage of that carbon in wood products, and the reduction of carbon release by the substitution of wood for steel and concrete building materials.
- Promote the reduction of estate taxes on forest land to promote inner generational working forest management planning and consolidation of working forests.
- Federal and state forest taxation systems that encourage long-term investment in sustainable forest management and habitat restoration, and that discourage parcelization.
- Small forest landowner assistance programs, such as the American Tree Farm Program or Forest Stewardship Program that educate and provide assistance on how to maintain working forests.
- Champion the re-analysis of the Northwest Forest Plan and completion of individual forest plans in order to re-balance the social, economic, and ecological benefits and products on a national forest specific basis.
- Promote regeneration timber harvests in Collaborative Forest Landscape Restoration Programs. [e]
- Support state and federal direct payment and cost share incentive programs.
- ESA reform that removes the unintended litigious consequence of private citizen enforcement and serves to provide incentives that encourage the management of and for endangered species rather than making it a liability.

a USDA Technical Report PNW-GTR-800. Washington's Forest Resources 2002-2006.

b Washington Trust Land Transfer Program. July 2011

c Sutherland, D. Bare, B.B., 2007. The Future of Washington Forests.

d Lackey, R.T., 2007. Science, Scientists, and Policy Advocacy. Conservation Biology 21(1):12-17.

e Franklin, J.F. Johnson, K.N. 2012. A Restoration Framework for Federal Forests in the Pacific Northwest. Journal of Forestry 110(8):429-439.

This position statement was adopted by the Washington State SAF Executive Committee on June 25, 2013, and will be submitted for an approval vote of its general membership during the 2013 fall elections. This statement will expire on June 25, 2018, unless it is renewed, revised, or withdrawn prior to that date.

HARRY BELL

Product and Process Environmental Improvement Analysis for Buildings (Carbon Life Cycle Assessment)

By Bruce Lippke

Life cycle analysis of house designs has shown that wood framing generally produces lower burdens than concrete or steel alternatives. How to select specific products or process changes (such as biofuel drying) to reduce environmental burdens is less obvious. Understanding the burdens imposed by specific products and processes can provide more direction.

Life cycle inventory data available from the National Renewable Energy Lab (NREL 2009) provides measures of inputs and outputs for every stage of the production of construction components. This fact sheet focuses on carbon emissions and the other green house gas outputs contributing to Global Warming Potential (GWP).

Using wood products provides a unique opportunity to store carbon from sustainably managed forests (Perez-Garcia et al 2005a). The carbon stored in the products offsets the emissions from processing the wood and potentially the emissions from other products used in construction assemblies. Using wood also substitutes for fossil-intensive non-wood materials, offsetting their emissions (Perez-Garcia et al 2005b).

Using the Athena Environmental Impact Estimator (ATHENA 2004) and data from the NREL USLCI database, we can analyze carbon impacts at the level of individual components and for construction assemblies. Figure 1 (bottom tier), starts with the carbon emissions from wood floor-joist components, dimension wood joist {Dim-Joist} and Engineered Wood Product I-Joists {EWP I-Joist}. Both products store carbon (negative emissions) because emissions from processing are more than offset by the carbon in the products themselves. In contrast, Concrete Slab and Steel Joists result in substantial carbon emissions (2-4 kgCO2/sq ft of floor).

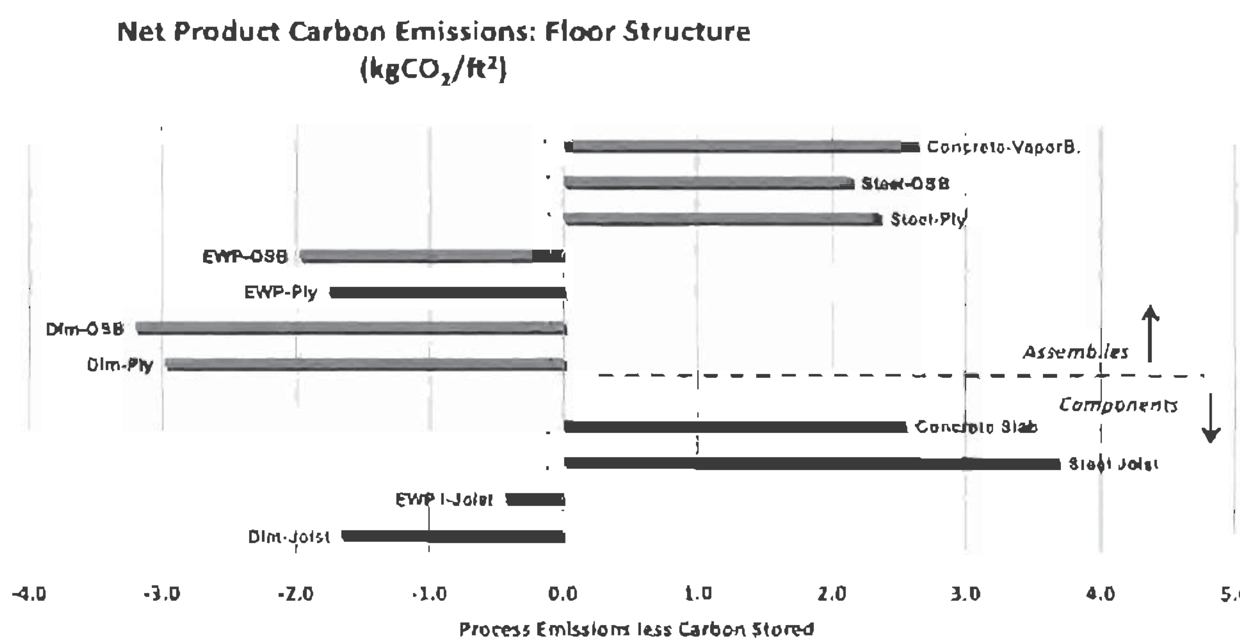


Figure 1: Process Emissions less Carbon Stored in Floor Structure Components and Assemblies from Lippke & Edmonds 2009.

Adding a wood covering, such as plywood {Ply} or oriented strandboard {OSB}) over steel joists (top tiers) does not completely offset the emissions from the heavy gauge steel that is used in flooring. Adding a vapor barrier (VaporB) to a concrete slab floor without a wood cover provides no offset. EWP I-joists with wood covering store less carbon than dimension joists because they use less fiber. However, all combinations of wood joist with wood covering store substantial amounts of carbon.

The reduction in GWP (carbon-equivalent global warming potential) for competing ***floor-assemblies*** is shown in figure 2. The EWP I-joist with an OSB cover displaces more GWP emissions than a Plywood cover alternative (top bars) because OSB is more dense, i.e. contains a little more carbon. The EWP I-joist with an OSB cover is better than concrete reducing GWP emissions by 3 $kg*ft^{-2}$ of floor (middle bars). Another measure of interest is the emission reduction relative to the fiber used. The EWP I-joist reduces CO_2 emissions by 4.6 kg per kg (dry weight) of wood used. The comparisons with steel (bottom bar) show the wood joist and cover reducing emissions by 9.8 $kg*ft^{-2}$. This is more than twice as effective as the substitution for a concrete floor because steel joists must be heavy gauge to minimize floor bounce. Because the steel floor also uses wood in the floor cover, it is slightly less fiber efficient, reducing emissions by 4.2 kg per kg of wood used. If there is an adequate supply of wood, greater use of wood will improve a construction-footprint the most. If not, maximizing the efficient use of wood fiber becomes a priority.

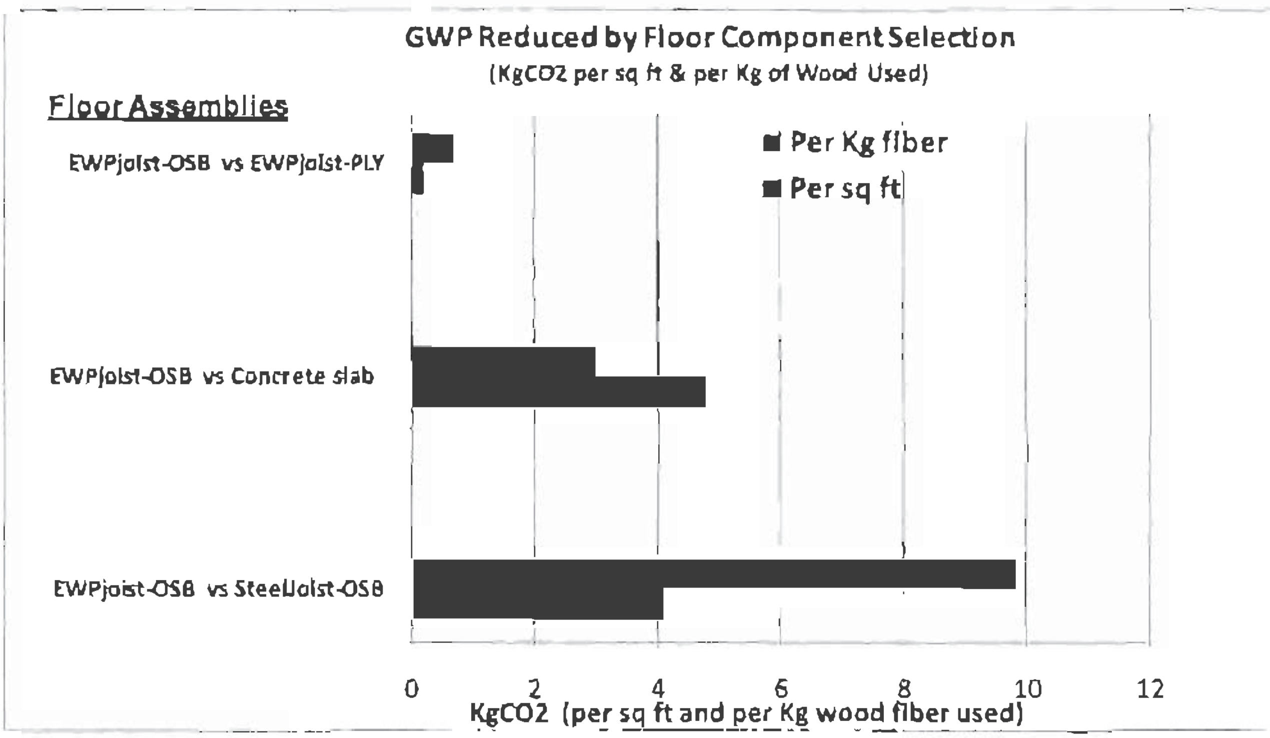


Figure 2: Reducing Global Warming Potential by Selecting Components in Floor Assemblies (per square foot and per kg of fiber) from Lippke & Edmonds 2009.

While displacing steel in floors is more 'carbon-effective' than displacing concrete, these findings cannot be generalized to wall assemblies. As noted in figure 3, the wood-wall *components* (kiln dried stud {KDStud}, Green Stud, Plywood, OSB, biofuel dried plywood {BioDryPly}) each store an amount of carbon that more than offsets their processing emissions. Some ***wall assemblies*** use sufficient amounts of wood to more than compensate for the carbon emissions of some non-wood components such as vinyl cladding. As a component in walls, concrete block substitutes not only for wood studs, but also for the wood sheathing and, with the addition of stucco, for any wood or vinyl cladding used with wood-framed walls. In terms of carbon emissions, the worst assembly is Concrete Block and Stucco, while the best configurations use biofuel-dried wood products (top three bars).

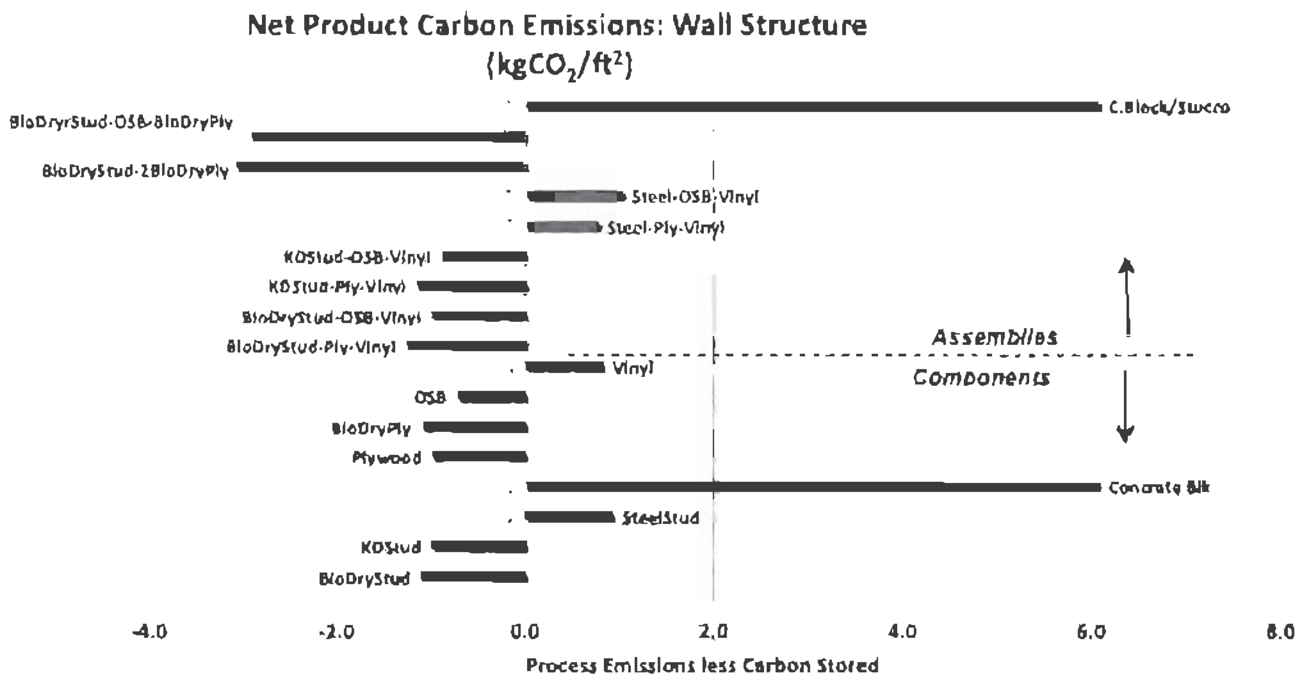


Figure 3: Process Emissions less Carbon Stored for Wall Components and Assemblies from Lippke & Edmonds 2009.

The carbon stored in an un-dried green stud is the same as for a biofuel dried stud but the latter uses more fiber as fuel. The benefit of using more biofuel is within easy reach for both wood studs and plywood (BioDryPly) but is not shown for OSB because it already uses more biofuel for drying. The assembly made of biofuel-dried-studs, biofuel-dried-plywood sheathing and cladding stores the most net carbon. There are many opportunities for product development to improve products and construction assemblies beyond these basic design options. There will also be some regional differences driven by regional energy sources and different wood species.

The reductions in GWP resulting from substituting competing wall designs are shown in figure 4. The biofuel dried stud with biofuel dried plywood in both sheathing and cladding substituting for the (more common) kiln dried stud, OSB sheathing and vinyl siding reduces GWP by 2.2 $kgCO_2*ft^{-2}$ of wall, with a fiber efficiency of 2.1 kg CO_2 reduction per 1kg of fiber used (top bars). The benefit of this substitution is almost the same as replacing a conventional steel wall assembly with a conventional wood assembly (bottom bars). If a biofuel dried stud wood wall replaces a steel framed wall assembly, the combined substitution effect is a GWP emissions reduction of 4.1 $kgCO_2$ per sq. ft. of wall, with a fiber substitution efficiency of 2.7 $kgCO_2$ per kg of wood fiber used. Using the wood designs in place of concrete and stucco walls results in GWP reductions of 7-9 $kgCO_2$ per sq. ft. of wall or and 3.5 $kgCO_2$ per 1 kg of wood fiber.

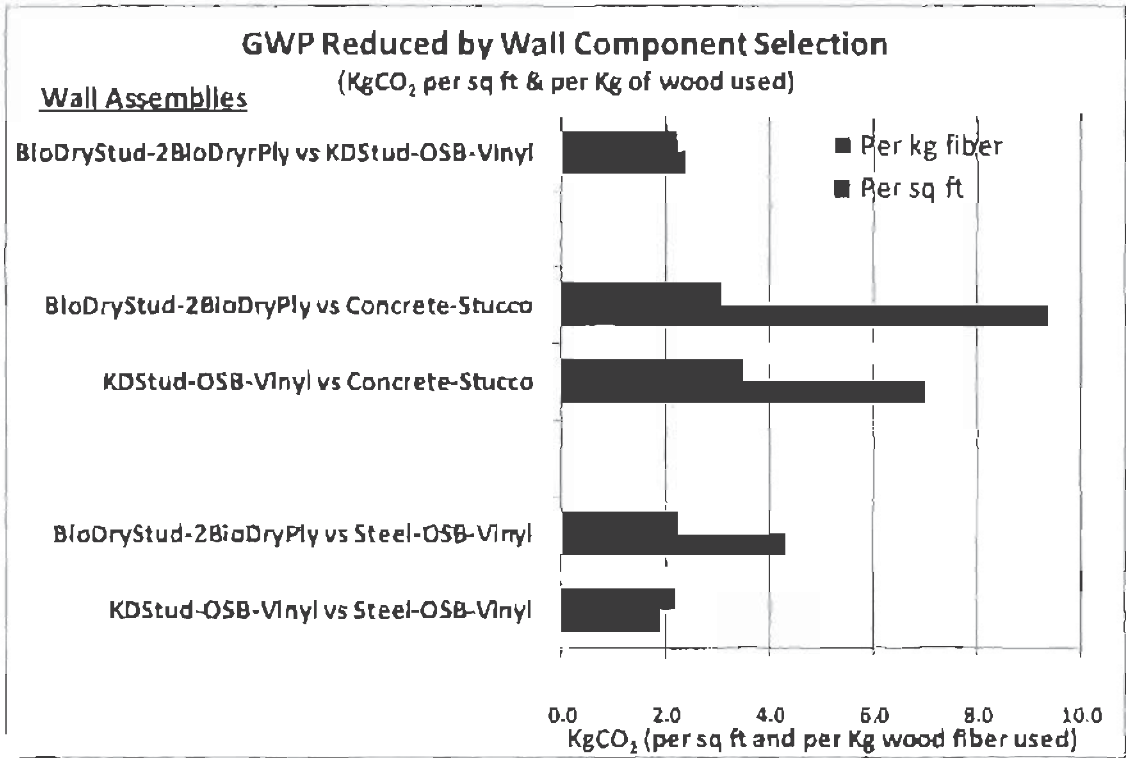


Figure 4: Reducing Global Warming Potential by Selecting Components in Wall Assemblies (per square ft of wall and per unit of fiber used) from Lippke & Edmonds 2009.

For wall and floor assemblies, the displacement of emissions per unit of wood fiber used is similar; however, wood-based options are more effective at displacing the carbon emissions from steel in floors and concrete in walls. Unfortunately, these differences generally are not identified or valued in market exchanges given the low value currently placed on carbon emissions from fossil fuels.

Environmental Improvement Opportunities

These results suggest there are product selection and product processing alternatives that can substantially reduce environmental burdens, as demonstrated here by GWP reductions. Use of wood in more building applications offers opportunities to avoid and offset fossil emissions from non-wood products. An understanding of net emissions from product alternatives based upon life cycle assessment is important for effective green building standards.

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October 17, 2013

Dear Task Force on Climate Change:

October 16, 2013 I submitted a letter providing arguments as to how solar energy could provide a solution to the problem of global warming and climate change.

Success begins with a National Energy Policy, Strategy, and Roadmap to guide the nation on a path toward an energy infrastructure primarily using solar as the energy source by 2050.

The Department of Energy (DOE) has the responsibility to develop a national energy strategy. DOE is also in charge of National Laboratories organized and chartered to provide technical support to address national problems. These Laboratories, including Pacific Northwest National Laboratory (Richland, WA) Idaho National Laboratory (Idaho Falls, ID), the National Renewable Energy Laboratory (Denver, CO), and Sandia National Laboratory (Albuquerque, NM) have strong technical organizations devoted to solving our nation's energy problem.

Action #1:

I request that Governor Inslee send a request to the Secretary of Energy, Steven Chu, and request National Laboratory development of a National Energy Policy, Strategy, and Roadmap. The draft Policy, Strategy, and Roadmap is to be submitted to the US Congress for approval and implementation.

Action #2:

I request that the Climate Change Task Force send a formal request to Pacific Northwest National Laboratory and the Department of Energy to conduct a Conceptual Design for a 3 to 5 gigawatt (electrical) solar farm located on the Hanford Site. This is consistent with the current 1.1 gigawatt (electrical) Columbia Generating Station Nuclear Power Plant located on the Hanford Site. A 3 gigawatt solar farm could make a significant impact on the electrical needs of the State of Washington.

I shall be happy to provide technical assistance to prepare these requests.

George A. Beitel

George A. Beitel, PhD

Port Orchard, WA 98366

I submitted this to Governor Inslee's climate change working group at climateworkgroup@ecy.wa.gov through the link on the Washington Environmental Council's website on October 16, 2013.

The technical solution to the problem of global warming and climate change is to convert to solar energy as the primary source for virtually all of our heating and electrical energy needs. Fossil fuel must be used only where absolutely necessary. Solar farms are a reality. The technology has been adequately developed thanks to 40 years of effort by the Department of Energy's Solar Energy Research Institute. Worldwide there are over 1000 solar farms today. Both Germany and China are aggressively building solar-electricity plants. In addition to the Department of Energy, excellent references supporting my position are listed at the end of my letter.

Solar energy is the only way to drive our society and industry by extracting energy that drives atmospheric warming with virtually no addition of carbon dioxide.

Most fascinating is that solar farms can harvest a "crop" worth $50,000 to $100,000 per acre per year with minimal water and no fertilizer as compared to $50 to $1000 an acre in the production of ethanol. The area of land devoted to our current ethanol production, could provide all of the electrical power being used in the US today. However, solar energy can be and should primarily be harvested from arid and semiarid lands with little agricultural value.

Some additional points:

- Solar can replace all coal fired power plants.
- Electric cars can reduce petroleum use, but
- Electric cars need more electricity from either coal fired plants or solar.
- Fossil fuels are too valuable to burn.
- Changing to solar will provide many jobs.
- Solar eliminates major sources of air pollution and global warming gasses.
- Solar farms have minimum environmental impact.

One square kilometer with 10% solar conversion rate could provide 100 million kWh/y of electrical energy with a retail value of $10 million. Current conversion efficiencies range from 5% to 30%. The State of Washington currently uses approximately 100,000,000,000 kWh of electrical energy per year. This is an annual equivalent of 1000 square kilometers of solar power. The Hanford Project has twice that amount of land in an essentially protected and unused status.

The technology is available. What is missing is a National Energy Policy and Strategy which is accepted and worked. I have tried several avenues to trigger the development of such a policy and strategy, with no success to date.

I have written a number of papers and letters to Senator Maria Cantwell and Representative Derek Kilmer with no significant impact so far. I have been corresponding with one of Representative Kilmer's staff for a year.

I have been trying to find the best approach since I retired some years ago. I spent 31 years working as a contractor to the Department of Energy as a Scientist/Engineer and an Affiliate Faculty with the University of Idaho and Idaho State University. I developed Systems Engineering and Environmental Engineering programs and courses and taught part time for 13 years.

I can readily provide more technical support and bases. Since I am retired I am doing this for future generations and am not seeking employment or financial gain.

George A. Beitel, PhD George A. Beitel

Port Orchard, WA 98366

References:

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Gerhard Knies, a retired German Physicist. Presentation on why and how Europe should go solar. http://213.133.109.5/video/energy1tv/Jan%20NEU/Konferenz/Wirtschaft/10,000_SGW/23_MS/23_04_MS_01_Knies_Intro-Chairman.pdf

A Web-based news Letter "Solar Energy News" published by Renewable Energy, at http://www.renewableenergyworld.com/assets/newsletter/solar.html

October 23, 2013

Solar Power – Full Speed Ahead

GEORGE A. BEITEL, PHD
PORT ORCHARD, WA

Objectives

- Reduce Atmospheric Carbon Dioxide
- Reduce Global Warming
- Reduce Ocean Acidification
- Obtain 80-90% of our energy from solar by 2031
- Develop a Solar Energy Based National Energy Policy, Strategy, and Roadmap

National Problems

- $16.7 trillion national debt and rising
- >7.7% unemployment, worse underemployment
- Global warming from fossil fuel usage
- Fossil fuels will run out: petroleum first, then natural gas, then coal
- Balance of trade from petroleum currently ~$300 billion/year
- Petroleum dependence involves unstable political relationships.

Solar can solve all these problems

- Solar can replace all coal fired power plants.
- Electric cars can reduce petroleum use, but
- Electric cars need more electricity from either coal fired plants or solar.
- Changing to solar will provide many jobs.
  - $100 trillion in new solar opportunities.
- Solar eliminates major sources of air pollution and global warming gasses.

Past objections to solar

- Capital costs too expensive
  - But costs are decreasing (DOE – 2010)
    - Coal fired plants - ~$3000/kW
    - Solar thermal - ~ $4500/kW
    - Solar Photovoltaic - $5000/kW
- Too land intensive
  - All US energy could be supplied by 7% of Arizona land area (GE solar website)
  - More prime farm land is devoted to ethanol production than would be required for all US energy from solar.
  - Washington State electrical energy could be supplied with solar cells on half of Hanford Site
- Only available for 10 h/day or less
  - Great opportunity for improvement
  - Solar thermal plants now provide 24/7 power using thermal storage.

Cost

- September 14, 2011, DOE guaranteed a $1.2 loan for a 250 MW solar plant, Mojave Solar Project.
- U.S. has about 1600 coal fired plants average power 250 MW.
- Since solar energy is collected only 10 h per day, we need 2.4 times as much installed power.
- It would cost about $4.8 trillion to replace all coal fired plants with solar power plants.
- Comparable investment would replace most petroleum needs.

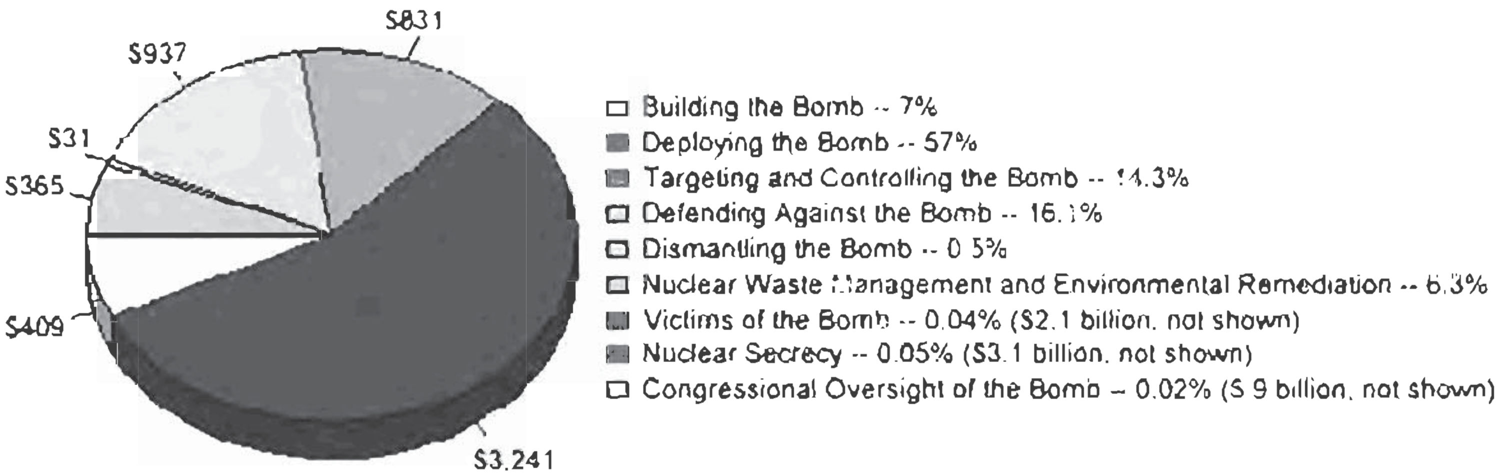
Cost comparison

- Nuclear weapons program cost $5.8 trillion through 1996 – Brookings Institute - 1998. This is ~$8 trillion in 2010 dollars.
- National Debt has grown by ~$11 trillion since GW Bush took office.
- Over the next 20 years, our balance of trade for petroleum will accumulate to >>$6 trillion possibly ~$17 trillion.
- NRDC estimates global warming annual cost at $1.9 trillion and increasing.

Nuclear weapons cost

Total: $5,821.0 billion

in billions of constant 1996 dollars



U.S. Nuclear Weapons Cost Study Project
Brookings Institution Press, 1998

Opportunities

- Coal costs (2009) ~1 billion ton @ $44/ton delivered = $44 billion/y
- Petroleum – 19 billion bbl/day @ $80/bbl = $550 billion/y
- Global warming - $1.9 trillion/y

Actions

- Request Department of Energy to prepare a National Energy Policy, Strategy and Roadmap
- Request Department of Energy and Pacific Northwest National Laboratory to a Conceptual Design for a 3 to 5 GW solar farm at Hanford
- Work with the Senate Committee on Energy and Natural Resources through Sen. Marie Cantwell

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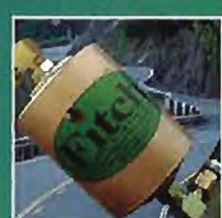

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www.fitchfuelcatalyst.com

APSI Inc. Advanced Power Systems International

Advanced Power Systems International, Inc., was founded in 1994 by John C. Fitch whose life is chronicled in the biography "Racing Through Life" by Carl Goodwin. A race car driver, road crash barrier designer and inventor, Mr. Fitch is a man of many firsts, as is the product that he contributed his name to - The Fitch Fuel Catalyst.

Advanced Power Systems' objective is to provide a product to the market that would constructively affect the environment and simultaneously have a positive economic impact for the end user.

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FUEL CATALYST

Fitch is a permanent fuel treatment device unlike any other product past or present on the market. This product transforms gasoline and diesel into a superior quality of fuel allowing a combustion engine to extract the maximum amount of energy with minimal emissions.

Fuel is most potent and produces the most energy when it is freshest. Fuel is most potent at the time of refining but unfortunately it doesn't remain at this high quality, it diminishes dramatically during storage and transportation. Treating gasoline or diesel with Fitch will re-refine the fuel, returning it to the most potent quality by reversing the natural degrading process and suppressing bacteria growth.

PERMANENT FUEL TREATMENT

AUTOMOTIVE

DIESEL FLEETS & CONSTRUCTION

RECREATION VEHICLES

OUTDOOR POWER EQUIPMENT

POWER GENERATION & HEATING

MARINE

AUTOMOTIVE

DIESEL FLEETS AND CONSTRUCTION

RECREATIONAL VEHICLES

OUTDOOR POWER EQUIPMENT

POWER GENERATION & HEATING

MARINE

What is the difference between a permanent fuel treatment and an additive?

An additive is usually a chemical added to fuel. Additives must be replenished at each refueling. A permanent fuel treatment affects the fuel but does not become part of it and does not need to be replaced.

What is the Fitch Permanent Fuel Treatment?

A metal alloy composed by a proprietary process that permanently transforms hydrocarbon fuels to a superior quality.

Can the Fitch Permanent Fuel Treatment harm my engine?

No. Fitch Permanent Fuel Treatment simply pre-treats the fuel before the combustion process increasing combustion efficiency and reduces the creation of pollutants.

How is this Permanent Fuel Treatment introduced to the fuel supply?

Outdoor power equipment and recreational vehicles use the Fitch "drop in" tank application. Simply unscrew the gas cap and drop it in. For automobile, Fitch offers a "Bolt on" system that is easily installed using "SAE & SLC" quick connect fittings or a "Drop in" tank application which is installed by accessing the fuel tank directly. Commercial applications are typically in line systems or multiple drop ins depending on fuel tank capacity and fuel flow rates.

Will the use of Fitch void a manufacture's warranty?

No. The federal law regulates warranties for the protection of consumers. The essence of this law concerning aftermarket parts is that an engine manufacturer may not deny a warranty based alone on the use of an aftermarket part.

Do I still need to use Stabil if I use Fitch?

The Fitch will keep the fuel fresh in the fuel tank, however, it cannot treat the fuel in a carburetor because it is not in contact with that area unless the vehicle is operated. When storing during off-season, we recommend running the carbs dry or starting the machine once a month to allow the treated fuel to run through the carbs.

INTRODUCTION

The Fitch® Fuel Catalyst (FFC) for marine diesel engines:

- Reduced Fuel Consumption
- Reduced Greenhouse Emissions
- Improved Combustion Efficiency
- Improved Overall Performance
- Provides a Cleaner Burn

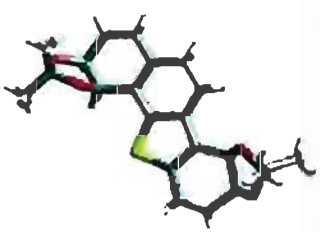
Independently tested to ASTM fuel standards, FFC treated fuel is superior in Cetane, Lubricity & molecular composition compared to untreated diesel.

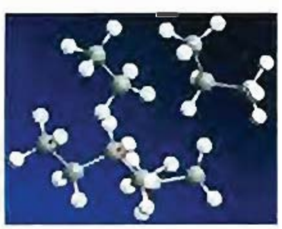
The FFC has an impressive list of Credentials including SAE, ASTM and Federal FTP-75 highway fuel economy/emission tests. It is widely used by the U.S. Dept. of Defense in multiple applications.

HOW DOES IT WORK

The Fitch Fuel Catalyst is a patented metallic alloy that reformulates fuel on board a vessel or vehicle prior to combustion. The FFC is easily retrofitted into an engine's fuel system between the fuel tank and the engine, modifying the molecular structure of fuel to a state where it is capable of more complete combustion.

What does it do to diesel fuel?





Reduces the concentration of Aromatics (left)
Increases the concentration of Aliphatics (right)
Releases more inherent BTU heat energy

BENEFITS

The Fitch Fuel Catalyst is an excellent fuel stabilizer which retards bacteria growth in water contaminated fuel.

Obvious reduction in visible smoke

The left engine – NO FFC installed
The right engine – FFC Installed

More Power and Torque too!

Testimonials

f/v Royal Dawn, San Diego, CA

"after my first set of Fitch units delivered 12% savings, I bought a new set which showed a reduction 1/2 gph at 1300 rpms in flat calm seas", ***Brent Bixler, Owner***

f/v Ocean Angel I, Moss Landing CA

"I was totally blown away when the constant vibration of a pipe next to the main engine suddenly stopped after starting the first time after installing the Fitch!", ***Frank Lombardo, Captain***

F.A.S. Seafood, B.C., Canada

"After experiencing the lowest all-time monthly fuel bill the first month after installing a Fitch unit on the ***f/v Ocean Pearl****, we quickly decided to equip the main and gen-set engines on all 8 boats in our fleet",* ***Bob Fraumeni, Pres.*** *"it was kind of a no-brainer!"*

f/v Ocean Pearl, Victoria, Canada

One of 8 vessels in F.A.S. fleet equipped with FFC on all main and aux. engines. This vessel has a CAT3512 main engine and twin Northern Lights gen-set engines.

Tri Marine Seafood, Bellevue, WA

After an 18-month study, one of the largest tuna production companies has decided to implement the FFC on its entire fleet of seiners and recommend product to its affiliated companies around the world.

f/v Cape May, American Samoa

*One of 20 vessels in Tri Marine fleet to be equipped with FFC, the **f/v Cape May** will become the first to have Fitch units installed on its main 3800hp EMD main engine, 4 Cat 3412 gen-sets, the fuel purifier pump for a 6,000 gallon day tank and the ship's skiff.*

Heavy-duty units

FHD series (5-120 gpm models)
HDG in line units (40-150 gph models)
Sleeve in tank units(max 125 gallons)

The FFC complies with Lloyds' Registry, ABS and U.S. Coast Guard standards. FFC units offer a ***permanent fuel treatment***. The metal alloy elements do not lose potency and never dissolve or deteriorate.

COST & PAYBACK

The Fitch® Fuel Catalyst is available for all commercial and recreational vessels and vehicles. Heavy-duty versions are warranted for 7 years or 10,000 engine hours.

Estimated Savings

$400 per 1000 gallons purchased*

*Using $4.00/gal avg. cost of fuel, 2,500 hours per year operation and a burn rate of 10 gallons per hour, a conservative estimate of annual fuel savings would be:

10% savings first year = $10,000
10% savings for 4 years = $40,000

20% savings first year = $20,000
20% savings for 4 years = $80,000

The Fitch unit has a typical payback on active commercial vessels of less than half a year. With a 10,000 hour warranty, the heavy-duty Fitch models will put money in your pocket for the years to follow.

REDUCE YOUR CARBON FOOTPRINT AND IMPROVE THE AIR QUALITY BY INSTALLING A FITCH FUEL CATALYST ON YOUR MAIN AND GEN-SET ENGINES.

Patent Protected & Made in the USA

"The Fitch Fuel Catalyst"

Save Up to 20% on Marine Diesel Fuel

Fitch® FUEL CATALYST

For a Greener, Cleaner Environment

Improve Fuel Quality
Improve Engine Efficiency
Reduce Fuel Consumption
Reduce Emissions & Soot

Contact Fitch Fuel Catalyst Marine Specialist:

Mark Phillips
Power Fuel Savers
Tel: (562) 537-0165

Website: www.pofusa.net
Email: mark@pofusa.net

Manufactured by: APSI
339 Main Street
Torrington, CT 06790
www.fitchfuelcatalyst.com

Made in USA

BBB

UL LISTED 37YC

INTRODUCTION

The Fitch® Fuel Catalyst (FFC) for diesel engines and oil burner applications:

- Reduced Fuel Consumption
- Reduced Greenhouse Emissions
- Improved Combustion Efficiency
- Improved Overall Performance
- Provides a Cleaner Burn

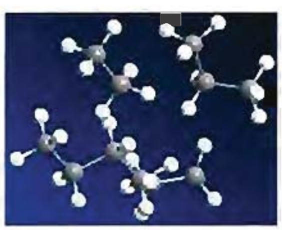
Independently tested to ASTM fuel standards, FFC treated fuel is superior in Cetane, Lubricity & molecular composition compared to untreated diesel.

The FFC has an impressive list of Credentials including SAE, ASTM and Federal FTP-75 highway fuel economy/emission tests. It is widely used by the U.S. Dept. of Defense in multiple applications.

HOW DOES IT WORK

The Fitch Fuel Catalyst is a patented metallic alloy that reformulates fuel to combustion. The FFC is easily retrofitted into an engine or boiler's fuel system after the fuel tank, modifying the molecular structure of fuel to a state where it is capable of more complete combustion.

What does it do to fuel oil(diesel)?



Reduces the concentration of Aromatics (left)
Increases the concentration of Aliphatics (right)
Releases more inherent BTU heat energy

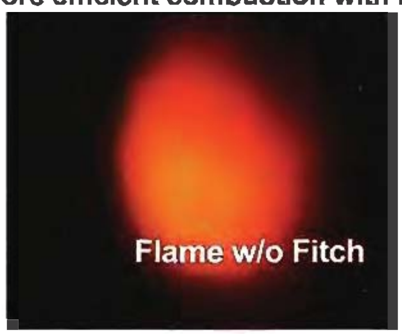
BENEFITS

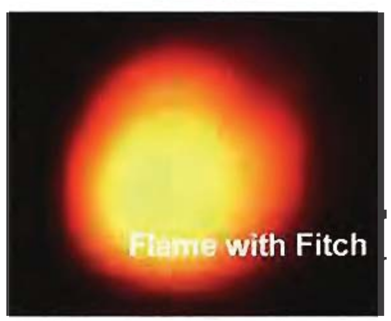
The Fitch Fuel Catalyst is an excellent fuel stabilizer which retards bacteria growth in water contaminated fuel.

Obvious reduction in visible smoke

NO FFC(left) verses FFC(right)

Visibly brighter flame
More efficient combustion with Fitch





Examples

Commercial/Residential Heating

Cleaner exhaust from cleaner burning fuel lowers costs

Heavy Equipment

Mining operation ore haulers use FFC to prolong equipment life and save minimum 5% on fuel costs.

Installed on Ore Hauler

Commercial Fishing Vessels

Fishing boats (independent and corporate fleets) from San Diego to the Bering Sea of Alaska have been using FFC on main and aux. diesel engines.

Heavy-duty units

The FFC complies with Lloyds' Registry, ABS and U.S. Coast Guard standards. FFC units offer a ***permanent fuel treatment***. The metal alloy elements do not lose potency and never dissolve or deteriorate. Heating oil reformers (not pictured) carry UL approval.

FHD series (5-120 gpm models)
HDG in line units (40-150 gph models)
Sleeve units(max. 125 capacity tank)

[redacted]

COST & PAYBACK

The Fitch® Fuel Catalyst is available for all heavy-duty engines and commercial boilers. Heavy-duty versions are warranted for 7 years or 10,000 operating hours.

Estimated Savings

$400 per 1000 gallons purchased*

*Using $4.00/gal avg. cost of fuel, 2,500 hours per year operation and a burn rate of 10 gallons per hour, a conservative estimate of annual fuel savings would be:

10% savings first year = $10,000
10% savings for 4 years = $40,000
20% savings first year = $20,000
20% savings for 4 years = $80,000

The Fitch unit has a typical payback of 20-40 times investment in most commercial applications. With a 10,000 hour warranty, the heavy-duty Fitch models will put money in your pocket for the years to follow.

Patent Protected & Made in the USA

"The Fitch Fuel Catalyst"

Save Up to 20% on Fuel Consumption

Fitch® FUEL CATALYST

For a Greener, Cleaner Environment

Improve Fuel Quality & Combustion Efficiency
Reduce Fuel Consumption, Emissions & Soot

Contact Fitch Fuel Catalyst Sales Rep:

Mark Phillips/Dennis Bradley
Power Fuel Savers
Website: www.pofusa.net
Tel: Mark @(562) 537-0165
Email: mark@pofusa.net or
Dennis @(760) 780-2200
Email: dennis@pofusa.net

Manufactured by: APSI
111 Upper Valley Road
Torrington, CT 06790
www.fitchfuelcatalyst.com

Made in USA

BBB

UL LISTED 37YC

University of Connecticut Center for Clean Energy Engineering

UCONN

INVESTIGATION OF EXISTING & DEVELOPMENT OF NEXT GENERATION FUEL REFORMING CATALYSTS FOR EFFICIENT ENERGY USAGE

SUMMARY OF WORK
AUGUST 2012

Hui Huang[a], Steven L. Suib[a], Michael Best[b]

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C2E2 – DOE Conference

Executive Summary – Abstract – August 2012

FUEL REFORMING CATALYSTS FOR EFFICIENT ENERGY USAGE

ENHANCEMENT OF COMBUSTION THROUGH SELECTIVE CATALYSIS OF GASOLINE AND DIESEL FUELS

Upgrading of commercial gasoline and diesel fuel will further enhance US energy resources.
Catalysis through chemistry has been greatly involved in improved environmental protection and economic growth. Greater than 90% of today's chemical processes have catalytic steps.

We have completed a series of experiments studying and measuring the ability of a novel catalyst to constructively modify commercial gasoline and diesel fuel. This catalyst has the ability to selectively remove hydrogen and or add oxygen to hydrocarbon components of fuel. The catalyst demonstrated the ability to produce reformed fuel species at room temperature which is novel and provides evidence these catalysts are broadly applicable in fuel applications.

The ability to selectively remove a few hydrogen atoms from specific sites is a key to the enhancement of fuel. Removing and redistributing hydrogen atoms from components of gasoline to produce olefins that can couple to form larger hydrocarbons has been measured. The ability of the same catalysts to introduce oxygen to hydrocarbons to form oxygenates has also been measured.

The combination of these two different reactions result in

- aromatic ring decomposition,
- coupling
- olefin formation, and
- oxegenation

simultaneously which is unique as regards chemical activity, constructive, and leads to enhanced combustion from the hydrocarbon fuel feedstock.

Data from our most recent experiments with small molecules that are model components of fuel have shown that chemical changes occur that involve the production of new types of bonds. These types of reactions have been demonstrated with some of the model fuel components of gasoline, heating fuel oil, and diesel fuel.

Data from combustion experiments demonstrated enhanced useful energy yield per unit of fuel.

2013 Clean Energy Roadmap: WASHINGTON STATE

Cascade Power Group
10900 NE 8th Street, Suite 1000
Bellevue, WA 98004
www.cascadepower.com

Updated by:
Chuck Collins, Project Manager
Date: October, 2013

Originally Published in March 2012

Table of Contents

Introduction

By law, Washington State must reduce greenhouse gas emissions to 1990 levels by 2020; to 25 percent below 1990 levels by 2035; and to 50 percent below 1990 levels by 2050 (RCW 70.235.020). The 1990 Greenhouse Gas Emissions Inventory established the 1990 baseline at 88.4 million metric tons of carbon dioxide equivalent (MMTCE). Therefore, by 2035 emissions must be below 66.3 MMTCE. Because current greenhouse gas emissions are at 85.27, we must reduce statewide emissions by 18.97 MMTCE by 2035 to reach these targets.[1]

In 2010, The Department of Commerce was directed by the legislature to identify priority areas for reducing greenhouse gas emissions while increasing competitiveness and keeping energy rates stable. The recommendations of the 2012 Washington State Energy Strategy (hereafter called the "State Energy Strategy") focus on transportation electrification, energy conservation in buildings, and distributed energy. The State Energy Strategy recommendations provide a cursory look at opportunities to reduce energy consumption and greenhouse gas emissions through waste heat recovery, electricity generation, and industrial operations.

This report outlines multiple scenarios that illustrate the impact of waste heat recovery, electricity generation and industrial policies on state energy load by 2035. These scenarios demonstrate ambitious but achievable pathways to meet our state's energy demands and emissions reduction goals while decreasing total energy consumption. This report is designed to complement the State Energy Strategy with specific thermal policy changes and illustrate the impact of these on Washington's energy future. We are not suggesting specific technologies over others, instead we are presenting a new way of looking at our energy system in Washington – and how we can make it better.

[1] **2012 Washington State Energy Strategy:** http://www.commerce.wa.gov/DesktopModules/CTEDPublications/CTEDPublicationsView.aspx?tabID=0&ItemID=10206&MId=863&wversion=Staging

WASHINGTON STATE ENERGY FLOW (2011)

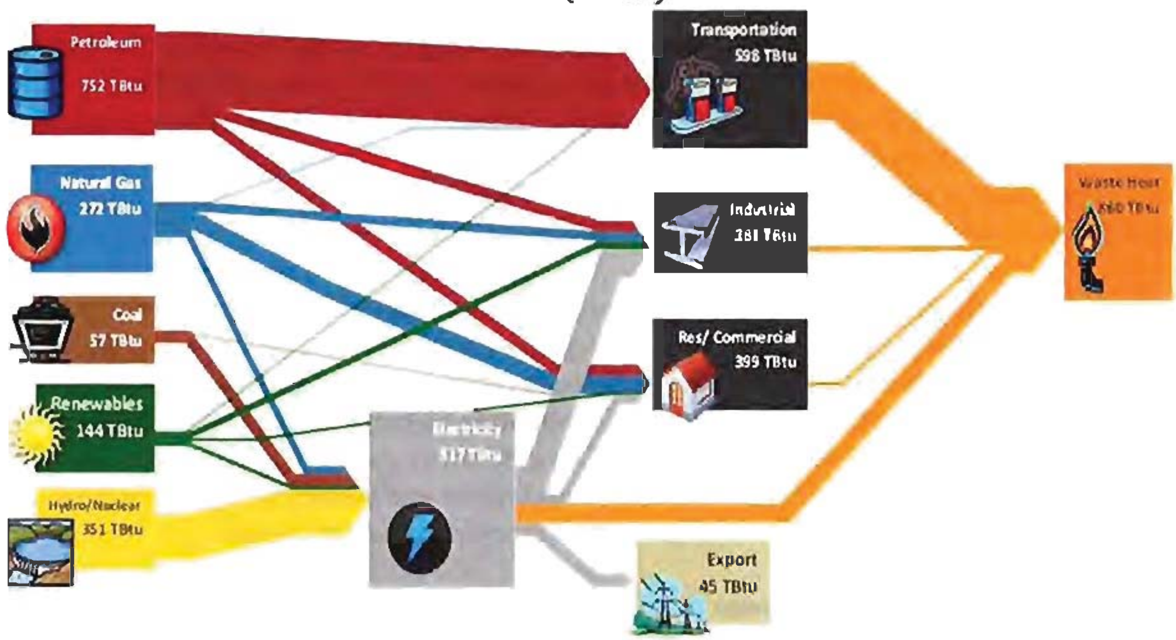

Figure 1. Energy Flows In Washington State In 2011. *Note: The boxes on the left denote primary energy sources consumed, and the boxes on the right show energy demand from the sectors of our economy.*

The energy flows, or the supply and demand of energy sources, in Washington for 2011 are represented In Figure 1[2]. In 2011, Washington State consumed 1,576 trillion British thermal units (TBtu) of energy. Of that, 517 TBtu were used to generate electricity, while the remaining 1,059 TBtu were delivered directly to the transportation, industrial, commercial and residential sectors.

A total of 860 TBtu, or 55 percent, of the total energy consumed in 2011 was lost as waste heat. The majority of the waste heat came from the transportation sector, which wasted 460 TBtu. Of the remaining waste heat, 272 TBtu come from electricity generation, 80 TBtu from Industry and 48 TBtu from the commercial and residential sectors. Most of the waste heat from electricity generation came from inefficiencies in fuel combustion, with a smaller amount lost through transmission and distribution lines. Waste heat from the Industrial, commercial and residential sectors was lost through primary energy consumption or end-use of electricity. Waste heat results from Inefficiencies in our energy system, but is also a free and largely untapped energy resource.

The 2012 State Energy Strategy focuses on transportation, building efficiency and distributed energy. However, this provides an incomplete roadmap for a comprehensive state energy policy. Electricity generation and industrial operations together account for nearly one third of the wasted energy in our state, yet receive very little attention in the State Energy Strategy. Waste heat recycling can meet growing energy demand and reduce the pressure on utilities to expand their generating capacity.

[2] http://www.eia.gov/state/analysis.cfm?sid=WA

Combined with the State Energy Strategy, the strategies presented here provide a more comprehensive approach for reducing energy consumption and greenhouse gas emissions.

STATE ENERGY RESOURCES

The energy landscape in Washington combines a diverse mix of renewable resources with almost entirely imported fossil fuels. As the state transitions from fossil fuels toward renewable energy sources, it is important to recognize the capacity of these renewable resources to meet our energy needs.

HYDROPOWER

In 2009, large hydroelectric dams on Columbia River and its tributaries provided 46 percent of Washington's electricity. Although it is unlikely that any new large hydroelectric will be built, the "US Hydropower Resource Assessment for Washington" conducted by Idaho National Laboratories found that improving the efficiency of 11 existing hydroelectric dams could produce an additional 875 megawatts (MW), or 13TBtu, each year.[3] Adding electricity production to existing non-power dams could generate another 1777 MW, or 26.5 TBtu, each year.

WIND

Washington currently has an installed wind capacity of 2,358 MW[4], with an additional 649 MW under construction and 2,784 MW under development.[5] The total wind potential in the state is 18,479 MW,[6] or approximately 190 TBtu, each year. According to the National Renewable Energy Laboratory, Washington's wind resources could supply nearly two-thirds of our state's electricity demand.

SOLAR

The solar resources in Washington range from approximately 2.5-5.0 kWh/m^2 each day.[7] This is more than enough to meet all of our state's energy demand. However, there is currently only 8 MW of grid-connected solar capacity and another 75 MW of utility-scale under development.[8] This does not include distributed solar systems that provide power directly to consumers and are not connected to the grid.

BIOENERGY

The "Washington State Biomass Inventory" has found that there is a total biomass capacity to produce 2215 MW, or 53 TBtu, each year.[9] Currently, there are 437 MW of installed biomass capacity, ranking Washington as tenth in the country in biomass capacity.[10] Most of the biomass used to produce power in this state is wood waste, but other sources include animal, municipal and food waste.

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[3] http://hydropower.inl.gov/resourceassessment/pdfs/states/wa.pdf
[4] http://www.nrel.gov/analysis/pdfs/51680.pdf
[5] http://www.rnp.org/project_map
[6] http://www.windpoweringamerica.gov/wind_resource_maps.asp?stateab=wa
[7] http://www.nrel.gov/gis/data_solar.html
[8] http://www.seia.org/galleries/pdf/Major percent20Solar percent20Projects.pdf
[9] http://www.pacificbiomass.org/WABiomassInventory.aspx
[10] http://www.nrel.gov/analysis/pdfs/51680.pdf

GEOTHERMAL

Much of Eastern Washington has good low-temperature (less than 100°C) geothermal resources, and there are more than 900 thermal wells in the Columbia River Basin. Currently, geothermal resources generate about 0.4 MW, or 0.011 TBtu, per year.[11] The U.S. Geological Society estimated in 2009 that in the next thirty years Washington would develop 7 to 47 MW of geothermal power.[12] The State's geothermal power policy expired in 2011.[13] In addition to electricity generation, geothermal energy can be used directly for ground source heating. There are over 7,800 MW of installed ground source heat pump units in the country, with an annual growth rate of about 15 percent each year.[14]

WAVE AND TIDAL

Although wave and tidal energy are not yet sending electricity to the grid, there are 135 MW of wave and tidal projects currently under development in Washington.[15] Collectively, Washington, Oregon and California have potential annual wave and tidal capacity of 167,428 MW, or 1501 TBtu.[16] Wave and tidal technologies are still in development and have not reached widespread commercial use.

INDUSTRIAL WASTE HEAT

Recycled waste heat from industrial operations and electricity generation has the potential to meet energy demands without needing to burn additional fossil fuels. The U.S Department of Energy's Northwest Clean Energy Application Center found that the technical potential for industrial (non-utility) combined heat and power (CHP) technology could generate 3,070 MW, or 73.4 TBtu each year.[17] Currently, there are 1,265 MW of installed CHP capacity at 34 industrial sites in Washington.[18] Recycling waste heat from power plants also has the capacity to generate a similar amount of energy and is covered in the next section.

THERMAL ENERGY TECHNOLOGIES

According to the U.S. Energy Information Administration (EIA), thermal energy consumption accounts for roughly one third of total U.S. energy demand.[19] Almost 80 percent of that thermal demand is used to provide heat below 150°C, which falls within the range of temperature produced by the following thermal technologies. By directly utilizing heat, thermal energy technologies lower the demand for primary fuel sources by recycling waste heat or displacing the need for electricity or fossil fuels to generate heat. Direct thermal use also lowers the grid demand for electricity to produce heat and therefore reduces losses along transmission lines. Thermal energy systems can operate independently from the grid, and are more resistant to extreme weather that can produce power outages.

[11] http://www.energy.wsu.edu/documents/geothermal.pdf
[12] http://www.energy.wsu.edu/Documents/WashingtonGeothermalEnergyStatusAndRoadmap.pdf
[13] http://apps.leg.wa.gov/RCW/default.aspx?cite=43.140&full=true
[14] http://geoheat.oit.edu/bulletin/bull28-2/art1.pdf
[15] http://www.rnp.org/project_map
[16] http://www.fas.org/sgp/crs/misc/R41954.pdf
[17] http://www.chpcenternw.org/NwChpDocs/WA percent20CHP percent20Technical percent20Potential percent2008 percent202010.pdf
[18] http://www.eea-inc.com/chpdata/States/WA.html
[19] http://pangea.stanford.edu/ERE/pdf/IGAstandard/SGW/2011/fox.pdf

Combined Heat and Power (CHP): A typical U.S. natural gas power plant is roughly 40-50 percent efficient, meaning less than half of the fuel input is fully utilized. The remaining energy is wasted as heat and vented into the atmosphere. Combined heat and power (CHP), also called high-efficiency cogeneration, generates electricity and re-usable heat from a single fuel source. The heat recycled by a CHP engine can be used for industrial purposes, to heat buildings in a surrounding area through a district energy loop, or sometimes to produce more electricity. As a result, CHP systems are approximately 70-80 percent efficient in using fuel to produce electricity and re-usable heat. Micro-CHP, or micro-cogeneration, units have an electrical output of less than 1MW and are used in single or multi-family homes and commercial buildings. By 2007, installed CHP capacity in the US was 85,000 MW and CHP produced 9 percent of U.S. electric power.[20]

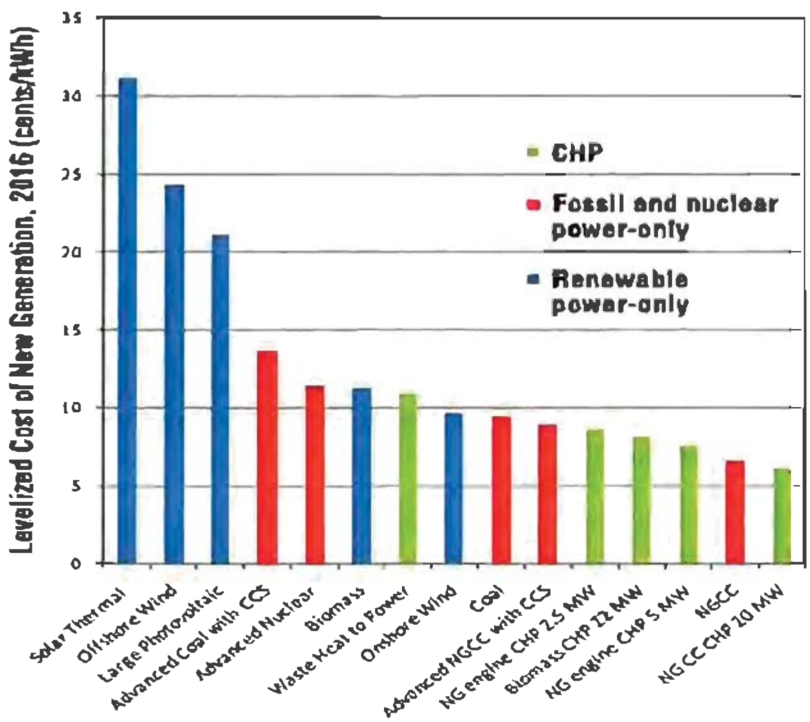

Figure 2. Levelized Cost of Greenhouse Gas Reduction for Generation Resources On Line in 2016[21]

As shown by Figure 2, CHP technologies can provide the cheapest greenhouse gas reductions. Likewise, the Oak Ridge National Laboratory has found that "CHP should be one of the first technologies deployed for near-term carbon reductions. The cost-effectiveness and near-term viability of widespread CHP deployment place the technology at the forefront of practical alternative energy solutions."[22, 23] On

[20] http://www.iea.org/files/CHPbrochure09.pdf
[21] http://www.districtenergy.org/assets/pdfs/Webinars/Webinar-4-7-2011/Mark-Spurr-Why-CHP.pdf
[22] http://info.ornl.gov/sites/publications/files/Pub13655.pdf
[23] For a description of various CHP technologies, see: http://info.ornl.gov/sites/publications/files/Pub13655.pdf

August 30, 2012 President Obama signed an Executive Order promoting CHP and setting a nationwide goal of 40GW of new CHP by 2020.[24]

Waste Heat Recovery (WHR): Waste heat recovery (WHR) recycles heat discharged as a byproduct of one process to provide thermal energy needed by a second process. WHR boilers use high-temperature excess heat to raise the temperature of fluid-filled tubes and produce a vapor, usually steam, which then powers a turbine to create electricity. The waste heat may come from industrial processes, wastewater treatment, livestock waste, fuel combustion and other sources. For the purposes of this report, WHR technologies that produce electricity are considered a type of CHP technology.

District Energy Systems: District energy systems produce steam, hot water or chilled water at a central plant, then distributed through a network of underground pipes to serve multiple buildings in an area, campus or district. As a result, individual buildings connected to a district energy system do not need their own boilers, furnaces, chillers or air conditioners. This allows district energy to achieve greater economies of scale and employ more efficient technologies. District energy systems can be run using a variety of fuels and provides greater reliability than electricity-based heating and cooling systems. As of 2009, Washington had 14 district energy systems with 538 MW heating capacity, or about 14.5 TBtu per year.[25] In the past few years, Washington produced surplus electricity when high river flows coincide with peak-wind production. This has resulted in 'negative-pricing' situations, where Washington must pay other states to take our electricity. Because district energy systems are fuel flexible, they can absorb excess energy to produce heat and serve as a 'virtual battery' for energy storage and dispatch. In Denmark, district heating plants are installing electric heating elements to produce hot water during off-peak hours or times of electricity surplus.[26] This reduces the need for fossil fuels to power district heating, further reducing emissions.

Solar thermal: Solar thermal systems use collectors to absorb the energy from the sun to produce heat, using either a fluid or the air to circulate the heat from outside the building to the inside. Solar thermal heat is generally used for heating water or for space heating. Passive solar buildings are designed to utilize the heat from the sun without mechanical or electronic devices. Key design features include window placement and type, insulation, thermal mass of building materials and shading.

Ground-source heating: Ground-source systems provide heating and/or cooling to buildings using the ambient temperature of the earth. In Washington the average ambient ground temperature is above 52° F.[27] Typically, a fluid circulates through a series of pipes and absorbs the heat from the earth in winter and carries it into the building. In the summer, the fluid carries heat from the air, which is absorbed by the earth to provide cooling. Ground-source heat pumps require electricity to circulate the fluid, which usually comes from the electric-grid or nearby gas-fired generators.

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[24] http://www.whitehouse.gov/the-press-office/2012/08/30/executive-order-accelerating-investment-industrial-energy-efficiency

[25] http://districtenergy.org/operational-data-2009-summary

[26] http://www.cdea.ca/sites/cdea/files/news/attachments/CDEA%20Report%20Final%20%20Dec%2015%202010.pdf

[27] http://geoheat.oit.edu/pdf/tp32.pdf

APPROACH

The 2012 Washington State Energy Strategy includes both near-term and long-term policy recommendations. The long-term horizon is based on forecasts out to the year 2035, which is slightly less than 25 years from now. Twenty-five years is a standard long-term time frame for energy forecasting, used by both the Energy Information Administration (EIA) and the Northwest Power and Conservation Council. The year 2035 also coincides with the first benchmark for Washington's greenhouse gas emissions goals, which requires emissions to be 25 percent below 1990 levels by 2035. The State Energy Strategy forecasts are based on EIA data and forecasts, but incorporate the effect of the new federal corporate average fuel economy (CAFE) standards, which require a 5 percent annual increase in vehicle fuel efficiency from 2017 to 2025. In the reference case in the State Energy Strategy, primary energy consumption increases by about 0.8 percent each year, whereas the population is forecasted to grow by 1 percent each year.

To be consistent, the 2035 scenarios presented in this report are based on the reference case in the Washington State Department of Commerce's "State Energy Strategy". However, the reference case was based on 2007 data, and so the values for energy demand in this report include updated information that is not in the State Energy Strategy. The previous version of this report uses the 2007 data as a base-case.

ASSUMPTIONS

In developing the policy scenarios for 2035, the following assumptions were made:[28]

- Coal is phased out of Washington electricity production by 2025, in accordance with the closure of the TransAlta plant in Centralia. (RCW 80.80.04)
- All new electric generating resources, including those under long term contract, meet a greenhouse gas emission performance standard equal to the industry average for natural gas combined cycle facilities. (RCW 80.80.040)
- The State Energy Codes adopted from 2013 through 2031 incrementally moves toward achieving seventy percent reduction in annual net energy consumption for new residential and commercial buildings by 2031. (RCW 19.27A.160)
- By 2035, the Energy Independence Act of 2006 requires 15 percent of electricity to come from renewable sources. Current law requires 15 percent renewables by 2020, so maintaining the same level by 2035 does not require policy change. (RCW 19.285)
- No changes in federal energy policy are made.

The scenarios in this report do not include any additional transportation efficiency improvements or building efficiency improvements, because the State Energy Strategy discusses these issues in detail.

[28] For a more complete list of existing policies related to climate change and energy, see: http://www.ecy.wa.gov/climatechange/laws.htm

Although advances in energy production technologies are likely to occur between now and 2035, the scope of these improvements are difficult to forecast, and are therefore not considered in this report.

In addition to these specific policy assumptions, the capacity factors in Table 1 were used to calculate the total amount of energy produced in a year (MWh or TBtu). Capacity factors represent the proportion of time that a facility is operating at full nameplate capacity (MW).

Table 1. Capacity factors for Renewable Energy Sources

Energy Technology	**Assumed Capacity Factor**
Wind Turbines (80 meter hub height)[29]	30%
Solar Photovoltaics[30]	20%
Biomass Boilers[31]	80%
Natural Gas power plants[32]	80%
Hydroelectric dams[33]	50%
Wave and Tidal power[34]	30%
Ground Source Heat Pumps[35]	20%
Micro-CHP (<1MW)	80%
District Energy Systems	90%

[29] http://www.windpoweringamerica.gov/wind_resource_maps.asp?stateab=wa
[30] http://www1.eere.energy.gov/maps_data/pdfs/eere_databook.pdf
[31] Ibid.
[32] http://www.nrel.gov/docs/fy00osti/27715.pdf
[33] Bowers, Rich. February 27th, 2012. Hydropower Reform Coalition. Personal Communication
[34] http://www.fas.org/sgp/crs/misc/R41954.pdf
[35] http://geoheat.oit.edu/pdf/tp32.pdf

2035 SCENARIOS

The following scenarios reflect changes to our state's energy system accomplished through specific policy changes. Each policy scenario is based on the 2011 reference case, and incorporates the changes of the previous one, demonstrating the cumulative impact of the proposed policies.

SCENARIO 1

In Scenario 1, all waste heat from natural gas combustion is utilized through CHP engines or district energy systems. Three-quarters of the recycled heat from electricity production is used by Industry, and the remainder is used for residential and commercial district heating. All natural gas consumed by the residential and commercial sectors use micro-cogeneration (1MW or less) or district energy systems. Additionally, petroleum consumed by the industrial sector decreases due to the relative high price of oil compared to natural gas, and the increased availability of waste heat for reuse.

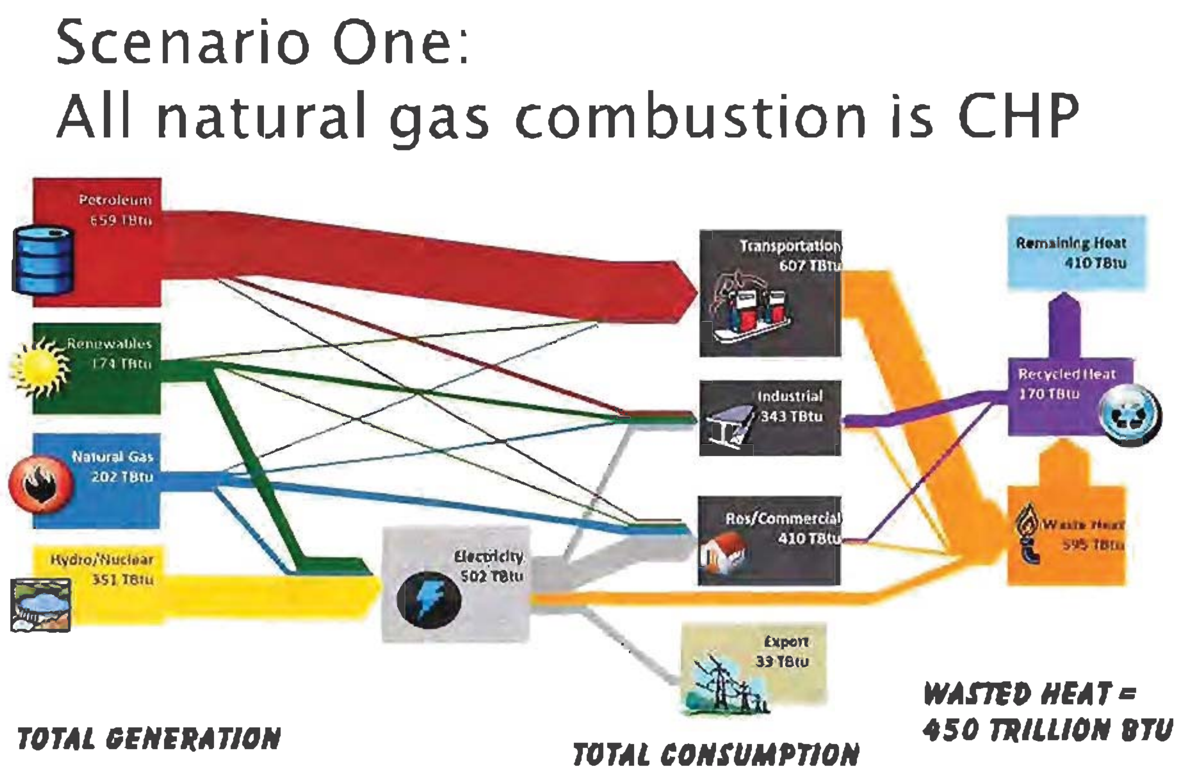

Figure 2. Energy flows in Washington in 2035 if all natural gas combustion employs CHP and/or district energy.

Scenario 1 demonstrates that by improving the efficiency of natural gas combustion we can meet our state's growing energy demands while lowering our total primary energy consumption. Combined with existing policy measures, this focused change can achieve 72 percent of the required greenhouse gas emissions reductions by 2035 (Table 2).

Table 2. Scenario 1 Energy System Changes from 2011 to 2035

	Change in Energy Consumption (TBtu)	**Change in CO2 (MMTCE)**
Petroleum	-93	-6,606,918
Natural Gas	-70	-3,737,875
Coal	-57	-5,290,929
Renewables	+30	0
Hydropower/Nuclear	0	0
Recycled Heat	+137	0
Total	-20	**-15,635,722**

To gain a more detailed picture of the energy resources that would be need to be developed for Scenario 1, projections for renewable and recycled heat development are shown in Table 3. Based on the total renewable potential discussed earlier and projected growth rates, 50 percent of the increase in renewable energy is met by wind, 35 percent by bioenergy, 5 percent from solar, 5 percent from ground-source heating and 5 percent from tidal projects. The amount of recycled heat generated is proportional to the amount of natural gas consumed by each sector, with the assumption that 75 percent of the recycled heat from utility operations is used by the industrial sector. The remaining 25 percent is used by the residential and commercial sectors through district energy systems.

Table 3. Scenario 1 Increases in Energy Resources

	Generation (TBtu)	**Capacity (MW)***
Wind	12	1,226
Bioenergy	11	460
Solar	2.3	382
Ground-source	2.3	382
Tidal	2.3	257
Total Renewables	**30**	
Utility CHP	33	1,380
Industrial CHP	55	2,300
District Energy	49	1,822
Total Reused Heat	**137**	

*Calculated using the Capacity Factors listed in Table 1.

The increase in energy produced with CHP would increase to about 7 percent, still lower than the national average of 9 percent. The scenario also shows a threefold increase in district energy capacity from 2011 to 2035. For comparison, Denmark transformed from being 98 percent dependent on imported fuel to providing heating for over 60 percent of all buildings in Denmark through district heating by 2007.[36] Similarly, district heating in Finland accounts for almost 50 percent of the total heating market. The examples from Denmark and Finland demonstrate that even greater expansion of district energy is possible, given commitment to a consistent policy framework.

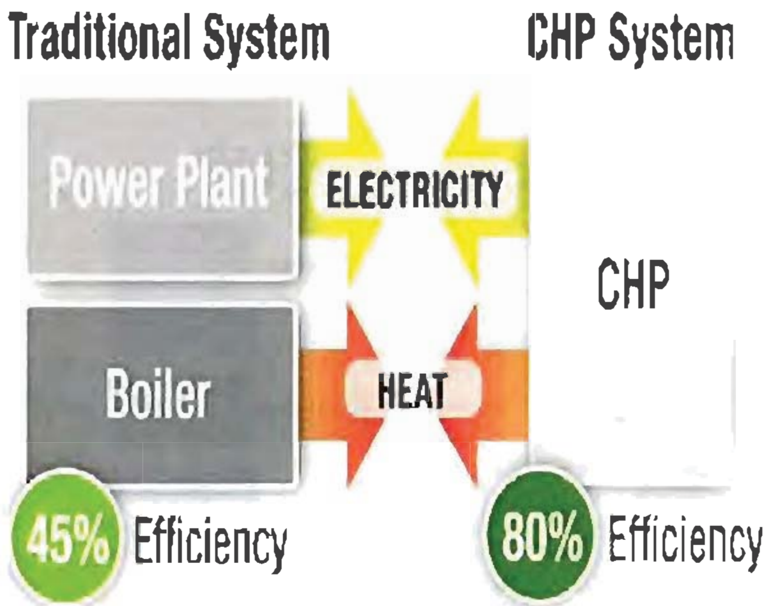

Figure 3. CHP Process Flow Diagram showing CHP system efficiency over boiler-based systems

[36] http://www.cdea.ca/sites/cdea/files/news/attachments/CDEA percent20Report percent20Final percent20 percent20Dec percent2015 percent202010.pdf

SCENARIO 2

Where Scenario 1 reflected a few targeted key policy changes, Scenario 2 illustrates a more comprehensive approach to reduce greenhouse gas emissions. In Scenario 2, all natural gas combustion employs CHP or district energy. Further, the state achieves full vehicle electrification, eliminating petroleum consumption from all uses except heavy transport and in rural heating and industrial applications.

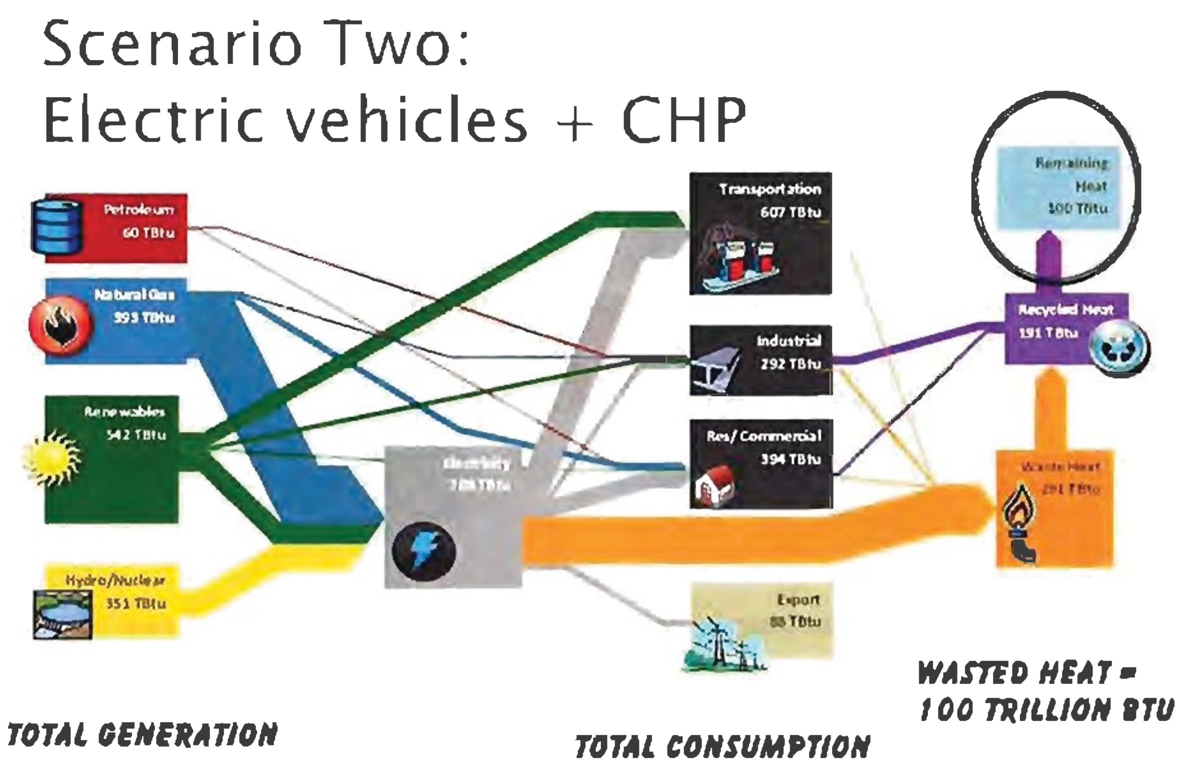

Figure 4. Energy flows in Washington in 2035 if all natural gas combustion employs CHP and/or district energy, with full vehicle-electrification in the transportation sector.

Scenario 2 requires almost quadrupling the amount of energy produced by renewable sources, as a direct result of full vehicle electrification. In this scenario, approximately half of the energy demand for electric vehicles comes from off-grid renewable charging stations, while the other half comes from grid-connected electric charging stations. The increase in electricity demand from the transportation sector of 9 TBtu and is offset by efficiencies achieved through CHP and district energy systems. Electricity demand increases by 271 TBtu, or about 52 percent, from 2011. Scenario 2 demonstrates that vehicle electrification requires a substantial expansion to the grid, if it is pursued in concert with recycled heat utilization.

It is important to note that transportation energy demand will likely decline with passenger vehicle electrification because electric vehicles achieve far greater efficiencies than internal combustion vehicles. Electric vehicle technology is expected to improve significantly by 2035, but is difficult to forecast. Therefore transportation demand was held at the same level as Scenarios 1 and 2. Many of the recommendations in the State Energy Strategy address transportation behavior through mass transit investment and pricing mechanisms. Vehicle electrification was chosen for this report because it holds the greatest potential for emissions reductions.[37] The increased efficiency of Washington's hydroelectric dams was not included in Scenarios 1 or 2 because it requires federal investment, the amount a scope of which is difficult to forecast. Technology improvements to renewable energy technologies as well as transmission infrastructure will allow for greater capacity and subsequently more projects coming online.

Taken as a whole, Scenario 2 reduces greenhouse gas emissions by over 66 percent by 2035, shattering the state goal of 20 percent by 2035 (Table 6). Total primary energy demand is 38 TBtu lower in Scenario 2 compared to 2011, due to the increased generation and transportation efficiencies.

Table 6. Scenario 2 Energy System Changes from 2011 to 2035

	Change in Energy Consumption (TBtu)	Change in CO2 (MMTCE)
Petroleum	-692	-49,244,506
Natural Gas	+121	+6,416,201
Coal	-57	-5,290,929
Renewables	+398	0
Hydropower/Nuclear	+0	0
Recycled Heat	+191	0
Total	**-38**	**-48,119,234**

Although the outcomes described in this scenario are ambitious they are also achievable through aggressive and comprehensive renewable energy development (Table 7). Due to the natural limit in biomass resources, bioenergy accounts for 20 percent of the increase in renewable energy, compared to 35 percent in the other scenarios. Solar makes up a larger proportion of renewable development, due to the distributed generation demands for vehicle electrification. Wind produces 45 percent of the increased generation, tidal produces 7 percent, and ground-source heating produces 3 percent.

[37] The remaining petroleum in Scenario 2 is consumed by aviation, rail, shipping and other heavy transportation.

Table 7. Scenario 2 Increases in Energy Production

	Generation (TBtu)	Capacity (MW)*
Wind	201	22,415
Bioenergy	80	3,345
Solar	72	12,044
Tidal	16	1,784
Ground-source	8	1,171
Hydropower	21	1,413
Total	**398**	
Utility CHP	57	2,384
Industrial CHP	77	3,220
District Energy	57	2,118
Total Reused Heat	**191**	

*Calculated using the Capacity Factors listed in Table 1.

Policy Options

The three scenarios described above describe a vision of Washington's energy future for the year 2035 that utilizes waste heat and reduces primary energy demand. A few key changes to our energy landscape can make significant headway in reducing greenhouse gas emissions while improving the efficiency of our energy consumption. The report now turns to the various policy pathways that enable this vision to take place. The following policy recommendations are complimentary to those in the State Energy Strategy and are intended to provide a menu of options that will help achieve the three scenarios.

Combined Heat and Power (CHP)

The most critical outcome of the three scenarios is ensuring that all natural gas combustion employs CHP systems to utilize recycled heat. CHP technology is mature and widely deployed in other parts of the country, but policy is needed in Washington to overcome barriers such as cheap electricity rates and interconnection costs.

1. Establish a heat-rate for all thermal-electric generation

In addition to simple waste heat recovery practices, a heat-rate should be set for all thermal-electric generation at power plants to a rate no higher than 5,000 Btu/kWh. This will encourage large-scale power plants owners to find ways to eliminate wasted heat by reusing it in industrial or district energy applications.

2. Revise key parts of I937 to include thermal energy

The Energy Independence Act (I937) is focused on electricity-based renewable energy and energy conservation projects. Recovery and reuse of wasted heat to displace fossil-fuel heating should be included as a qualified energy conservation resource. In addition, the applicability of 'high-efficiency cogeneration' projects only toward retail electric customers should be expanded to include utility companies, third-party owners, and other property owners.

3. Expand the output-based emissions performance standard

Washington currently has an output-based emissions standard (RCW 80.80.040), where all new electric generating resources, including those under long term contract, are required to meet a greenhouse gas emission performance standard equal to the industry average for natural gas combined cycle facilities. Expanding the output-based emissions standard beyond base-load generating facilities to include all grid-connected, non-emergency generating facilities would greatly accelerate the deployment of CHP technology due to lower allowable emissions limits. Broadening the use of output-based emissions standard for non-utility generating facilities would result in CHP deployment in the industrial sector as well.

4. Create mandatory energy conservation targets

Under the Energy Independence Act (I937), regulated utilities are required to "pursue all available conservation that is cost-effective, reliable and feasible." The utilities must develop aggressive conservation goals and targets, and are allowed to count high-efficiency cogeneration (CHP) for a retail customer toward those targets. The creation of mandatory energy conservation targets would encourage I937-compliance by looking beyond technologies and instead taking a more holistic view of energy waste. Similar to Renewable Energy Credits (RECs), which can be produced and sold by utility and non-utility energy generators alike, Energy Conservation Credits would create additional market value for certified energy conservation projects and allow utility companies to meet mandatory targets.

5. Require utility companies to consider CHP and District Energy in Integrated Resource Plans (IRPs)

Under RCW 19.280.030, utilities are required to complete Integrated Resource Plans that "explain the mix of generation and demand-side resources they plan to use to meet their customers' electricity needs in both the short term and the long term." These plans may include high efficiency cogeneration (CHP), but do not require inclusion of CHP and district energy potential. Requiring utilities to objectively consider CHP and district energy resources in the planning process would help shift the focus from building new generating capacity to using energy more efficiently.

6. Adjust process for setting standby rates for CHP systems

Utility customers with onsite generation typically require electricity from the grid, sometimes at variable levels. As a result, utility companies must have additional capacity to meet the maximum demand from these customers and are charged as a 'standby-rate'. Utilities typically charge standby rates to cover the cost of maintaining additional resources. The U.S. Environmental Protection Agency (EPA) has found that most states, including Washington, do not have standby rate structures that value the costs and benefits of CHP systems.[38, 39] The American Coalition for an Energy Efficient Economy (ACEEE) has found that best practices for standby rates include: rates weighted toward energy charges rather than demand charges; demand charges based on the probability of an emergency outage at a CHP facility coinciding with a period of peak grid demand; and elimination or limitation of demand ratchets.[40]

7. Require waste heat utilization at industrial facilities

One of the policy drivers in Denmark that led to widespread industrial deployment of CHP and district energy technology was a requirement that all industrial facilities utilize waste heat. Adopting a similar requirement in Washington could include recycling waste heat from industrial operations, using district energy to provide heating and/or cooling to industrial buildings, and installing CHP engines on generation equipment. While this is a more direct mechanism for recycling waste heat than many of the other policy options mentioned in this report, it proved highly effective in not only reducing industrial waste heat, but also shifting the organizational values of industrial companies in Denmark toward sustainability and waste management.

8. Convene a CHP working group

[38] http://www.epa.gov/chp/documents/standby_rates.pdf
[39] http://www.epa.gov/chp/state-policy/utility.html
[40] http://aceee.org/sector/state-policy/toolkit/chp/standby-rates

As CHP projects emerge, new barriers and obstacles may need to be addressed by stakeholders and policy-makers. The Department of Commerce should convene a CHP working group to identify barriers to deployment, share best practices and develop further recommendations for state action to support CHP deployment in target markets.

District Energy

Due to cheap electricity, electric resistance heating has become the standard for new building construction, despite the fact that district energy can provide building owners and tenants with more reliable and lower cost heating. Policy support is needed to support investment in district energy systems in favor of the current industry standard of electric heating. Local governments have a major role in supporting district energy and the International District Energy Association (IDEA) and National Trust for Historic Preservation have excellent resources for local policy-makers.[41] There are several key state actions that will encourage greater investment in district energy systems.

9. Allow utilities to rate-base investments in district energy and CHP

District energy systems provide customers with lower energy rates over time, but most of the costs are in the initial construction. Therefore, re-authorizing legislation to allow utilities to recover the cost of district energy and CHP project construction will help spread out the cost over time and reduce the financial risk to utilities.

10. Include district energy consideration in the Evergreen Sustainable Development Standard

The Evergreen Sustainable Development Standard (ESDS) is a building performance standard required of all affordable housing projects or programs that receive capital funds from the Housing Trust Fund. Projects receiving ESDS funds are required to meet energy efficiency and heating and cooling standards. The ESDS should require evaluation of district energy compatibility for the housing projects supported the Housing Trust Fund. Some sites will be compatible with district energy, whereas others will not be. Regardless, requiring an assessment of district energy compatibility will help familiarize project developers with district energy systems.

11. Provide guidance for county and local government to develop Heat Maps for planning

The State can assist local governments in planning for district energy systems through support and guidance on creating thermal energy maps for local development. Heat maps can be used to site industrial and commercial facilities with high thermal loads near facilities that generate useful thermal energy. This facilitates the development of district energy systems by locating thermal sources near thermal consumers. Additionally, it provides incentive for facilities with high thermal needs to locate in a particular city. The Department of Commerce should develop model guidelines from local governments to create heat maps and help simply permitting requirements.

[41] http://districtenergy.org/assets/pdfs/White-Papers/CommEnergyPlanningDevelopandDelivery2.pdf and http://www.preservationnation.org/issues/sustainability/green-lab/additional-resources/District-Energy-Long-Paper.pdf

12. Update State Energy Code to support district energy

The Washington State Residential and Non-Residential Energy Codes will incrementally require efficiency improvements in new buildings and building modification. Although district energy systems are more energy efficient that electric baseboard heating and individual furnaces, the efficiency standards in the State Energy Codes only set efficiency standards for heating technologies. The standards should be updated to increase the efficiency required of electric resistance heating compared to hydronic (district energy) systems.

13. Convene a District Energy working group

As cities around the state explore and invest in district energy, there is a distinct need for coordination and sharing best practices. This type of communication should not be limited to cities in close proximity to each other. The Department of Commerce should convene a district energy working group that involves city planners, private developers and utilities to identify barriers to deployment, share best practices and develop further recommendations for state action to support district energy development.

Fuel Oil

Although the relative high cost of oil compared to natural gas, electricity and district heating will likely reduce new installations that use fuel oil, phasing out existing petroleum-based heating systems will require policy action.

14. Establish output-based performance standards for industrial facilities

As discussed above, broadening the use of output-based emissions standard for non-utility generating facilities would result in CHP deployment and the reduction of petroleum fuels for industrial processes. Like the existing standard for base-load generation facilities, an industrial standard could be phased in to apply to new construction and to major equipment modifications. As facilities replace or upgrade equipment, petroleum fuels would be gradually eliminated from the industrial sector.

15. Update State Energy Codes to phase out fuel oil heating for new buildings

The Washington State Residential and Non-Residential Energy Codes will incrementally require efficiency improvements in new buildings and building modification. Natural gas furnaces, electric resistance heating and district heating are all more efficient and produce lower emissions than fuel-oil heaters. The State Energy Codes should phase out all fuel oil heating, because efficiency improvements to fuel oil heaters will not be sufficiently cost-effective to reduce greenhouse gas emissions and other pollutants.

16. Require retrofits when buildings change owners

While updates to the State Energy Code would take effect when there are major equipment modifications, another option to reduce fuel oil heating is through requiring equipment upgrades when buildings undergo a change in ownership. The cost of upgrading the heating system can be integrated into the selling price of the building, reflecting the increased value from more efficient and less polluting heating.

17. Require disclosure of building energy consumption, cost and fuel mix

The City of Seattle passed an ordinance requiring all buildings of a certain size to benchmark and report their energy performance. This information will allow for comparison between similar buildings and can inform decision-makers regarding purchasing, leasing or financing the buildings. A similar requirement should be adopted statewide to ensure that the energy performance, including the fuel mix, of our state's largest buildings is public knowledge.

Distributed and Renewable Energy

Some policy vehicles to help achieve the 2035 scenarios are not technology-specific and apply to distributed energy as a whole. Although existing policies require 15 percent of electricity to come from renewable sources by 2020, the significant increase in electricity demand due to transportation electrification will require additional policy support to deploy the needed scale of renewable technologies and infrastructure.

18. Revise distributed generation interconnection rules

The Utilities and Transportation Commission (UTC) sets interconnection requirements for generating facilities with a nameplate generating capacity of less than 20MW (WAC 480-108), however, the existing categories are insufficient to fully promote the development of distributed energy systems, including combined heat and power. Net metering policies should be consistent with the tiered-system recently established, to simplify the approval process. Additionally UTC should convene an ongoing stakeholder group to identify priorities for updating the interconnection rules, address new technologies and develop recommendations for the next revision of the interconnection rule.

19. Include thermal energy in state financial incentives

Many financial incentives for distributed energy exist, but most of them focus on electricity generation or specific technologies.[42] Incentives could include tax credits, exemptions or reductions; guaranteed or low-interest loans; grants or direct subsidies; and research, development and demonstration funding.

20. Study the benefits of distributed generation

Line losses along high-voltage transmission lines are a real source of wasted energy. A 2010 Carnegie Mellon Study found that 1MW of distributed generation can displace 1.2 to 2.25 MW of grid-connected generation, depending on siting.[43] As utilities seek to meet their conservation goals, they should be given

[42] See page 138 of the State Energy Strategy for an overview of distributed energy incentives. For a more detailed description of the incentives see:
http://dor.wa.gov/content/findtaxesandrates/taxincentives/incentiveprograms.aspx#Energy
[43] Nazari, M.H. October 2010 "Enhancing Efficiency and Robustness of Modern Distribution Systems" Carnegie Mellon Departments of Engineering & Public Policy and Electrical & Computer Engineering.

credit for reducing transmission losses. This could take the form of a multiplier for distributed generation that is applied toward conservation goals, or through some embankment of RECs or Energy Conservation Credits (EECs).

21. Require BPA to give priority to district energy systems to absorb surplus electricity

In recent years, negative pricing situations have resulted in lost revenue and inefficient management of renewable energy resources. District energy systems are fuel flexible and can provide thermal energy storage during times of surplus electricity production. The Bonneville Power Administration is responsible for managing the Northwest transmission system and has the authority to shut down certain generating facilities or export excess electricity. Federal action would be necessary to require BPA to offer surplus electricity to in-state district energy systems before exporting electricity to other states. This change would take advantage of intermittent renewable energy resources that are currently being wasted.

Transportation

Reducing waste heat, and therefore lowering primary energy consumption and greenhouse gas emissions, from the transportation sector is one of the most effective ways to improve the performance of Washington's energy system. Scenario 2 illustrates the emissions reduction potential of full electrification of motor vehicles, which will require strong commitment from state policymakers. Because the electric vehicle market is emerging, many of the policies described in the State Energy Strategy will assist electric vehicle deployment in the short-term, including: investing in electric vehicle charging stations; streamlining permitting for charging stations; and financial incentives for electric vehicle purchases and private charging station investment. Further studies into system reliability and infrastructure changes are needed to determine long-term policy recommendations.

CONCLUSION

In order to meet the greenhouse gas emissions reductions as required by law (RCW 70.235.020), Washington policymakers need to consider the full range of clean energy resources. The State Energy Strategy provides a solid foundation of policy actions related to transportation, building efficiency and distributed energy. The cumulative impact of those policies is uncertain. Instead of building a strategy based on policies to see how far they get us, the State should begin with a vision of its energy future and identify the necessary policies and projects to reach that vision.

This report outlines multiple visions for Washington's energy system in 2035 based on utilizing wasted thermal energy. The simplest of those visions achieves 21 percent of the emissions reductions needed by 2035, simply by capturing and recycling the waste heat from natural gas combustion. The most ambitious vision achieves 66percent of the 2035 emissions reduction goal, comprehensively transforming the state energy system and our air emissions profile.

Committing to using clean energy technologies will not only reduce our impact on the climate, but diversify our energy supply, keep energy spending in the state economy, spur job creation, and create a world-class business environment. That future is achievable, but it requires state action and leadership to make it a reality.

Employment Effects of Investing in Select Electricity Resources in Washington State

Prepared for Sierra Club

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CONTENTS

1. INTRODUCTION AND SUMMARY OF RESULTS

This study presents an overview of the current electricity portfolio in Washington State, a brief discussion of the state's potential for renewable energy and energy efficiency growth, and a comparison of the employment effects associated with investing in several types of resources in the state including solar, wind, energy efficiency, and natural gas. This analysis is intended to help readers understand the potential job creation of replacing the electricity from out-of-state coal generation.

Synapse developed estimates of spending on capacity, generation and energy efficiency measures based on current data for Washington generation and efficiency programs and our estimate of future costs. We used the IMPLAN input-output model to estimate the direct, indirect (i.e. suppliers) and induced (i.e. worker re-spending) activities that would occur in Washington from the construction and operation stages for these resources. Finally, the job impacts were developed on a per-average-megawatt (aMW)[1] basis to enable direct comparison between resources. Further detail on the assumptions and methodology is provided in subsequent sections of this report.

Another important consideration is the impact on rates associated with various energy resource portfolios. A recent study from the Beacon Hill Institute and Washington Policy Center estimated a large increase in rates due to the state's renewable portfolio standard.[2] However, previous work by Synapse evaluating the model used in that study shows why these impacts may be overstated.[3] Also, while our analysis does not include the impacts of increased costs on rates, it also does not include the decrease in energy bills that would accrue to energy efficiency participants and the impacts of the related re-spending of that savings in the state's economy. This study is simply meant to compare the job impacts of capital investments and operations and maintenance (O&M) for electricity resources.

The resulting job-year impacts (i.e. the equivalent of one job per year) per aMW for construction and installation are presented in Figure 1. These represent the impact from short-term activities of building new generating capacity and installing energy efficiency measures. Solar photovoltaic (PV) has the largest impact per aMW by far with 173 job-years for commercial and residential projects and 83 job-years for utility-scale projects—the latter is smaller due to economies of scale when installing large projects. The large impacts from solar PV (relative to other resources) come as a result of the labor-intensity of these installations. The utility-scale solar projects were assumed to be located in eastern Washington which has better solar resources than in the western part of the state. Energy efficiency installation--another labor-intensive activity—generates the next highest factor with an estimated 32

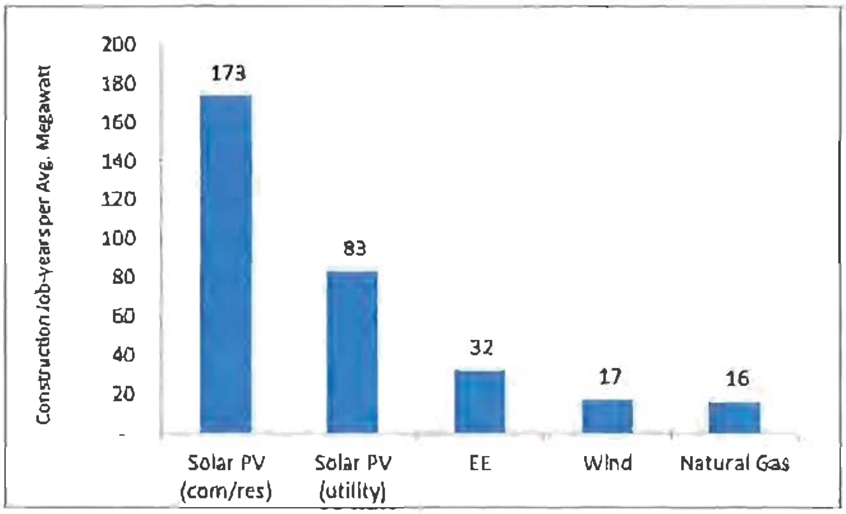
[1] An average megawatt (aMW) represents the average energy generated per hour over the course of a year (i.e. one aMW is equal to 8760 megawatt hours (MWh) per year).

[2] Beacon Hill Institute and Washington Policy Center. 2013. The Economic Impact of Washington State's Renewable Portfolio Standard. April 2013.

[3] Synapse Energy Economics, 2013. Not-so-smart ALEC: Inside the Attacks on Renewable Energy. Prepared for Civil Society Institute. Available here: http://www.synapse-energy.com/Downloads/SynapsePaper.2013-01.CSI.ALEC-Talking-Points.12-092.pdf

total job-years per aMW saved. Wind construction generates slightly more activity than natural gas—17 job-years per aMW compared to 16, respectively. Coal is not shown here since there are no new coal plants proposed in Washington.

Figure 1 – Plant Construction and EE Installation Job-years per Average Megawatt

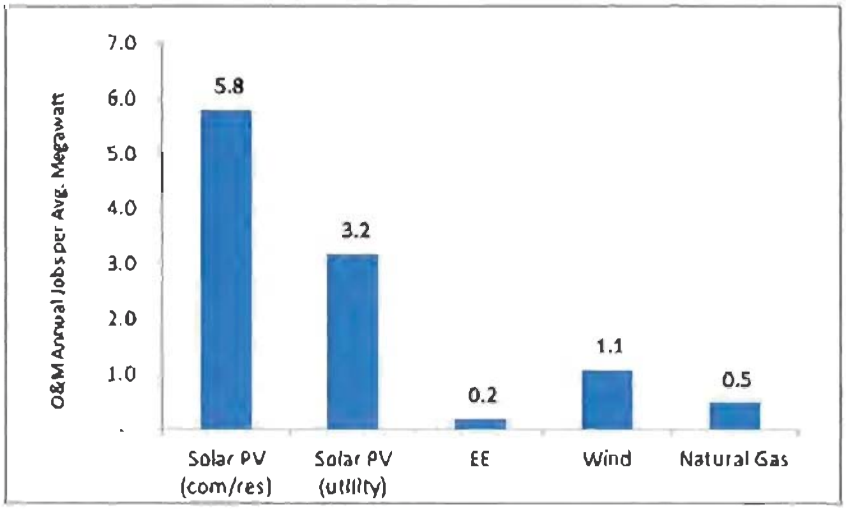


Source: Synapse and NREL JEDI Model (industry spending patterns), IMPLAN (industry multipliers)

The job impacts per average megawatt for O&M and fuel are presented in Figure 2. These represent the impact from long-term activities needed to run generating facilities each year. Again, solar PV has the largest impact of any resource with 5.8 jobs per aMW for residential and commercial projects and 3.2 jobs per aMW for utility-scale projects. Wind generation creates more O&M activity than natural gas in the state—1.1 to 0.5 jobs per aMW, respectively. Wind power involves more labor-intensive O&M activities and, unlike natural gas, requires no fuel spending (which would mostly leave the state). Energy efficiency incurs little O&M costs, those shown here represent the on-going marketing and administration of EE programs averaged over a twenty-year period.

This study did not evaluate the impacts of coal O&M since the only operating plant in Washington (Centralia) is slated to retire in 2025. Coal generation that is brought in from out-of-state (e.g. from the Colstrip plant in Montana) generates no direct jobs in Washington, by definition. Therefore, any replacement energy produced in Washington will bring in net new jobs to the state.

Figure 2 – Annual Operations and Maintenance (including fuel) Jobs per Average Megawatt



Source: Synapse and NREL JEDI Model (industry spending patterns), IMPLAN (industry multipliers)

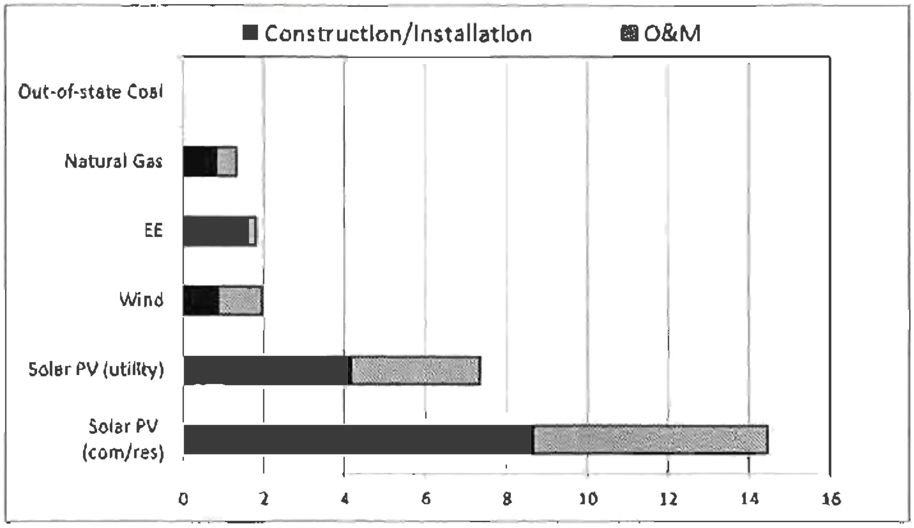
Table 1 and Figure 3 show the job factors for each resource when combining the construction and O&M stages. The "total" column in Table 1 combines the average impacts at both stages, averaged over a 20-year period to present a convenient comparison of the job impacts of each resource from "start to finish." Solar PV creates the highest impacts per aMW (14.4 for rooftop projects and 7.3 for utility-scale projects) while wind and EE have similar levels of job impacts—1.9 and 1.8, respectively. Natural gas creates the lowest average job impact of any new resource with 1.3 jobs per aMW. A state energy portfolio should not be based on these results alone–solar PV creates the most jobs per aMW but cannot fully replace lost generation from coal on its own. However, this analysis can be used to estimate the job impacts the state could expect from a cleaner energy portfolio by applying the impacts to the amount of aMW added for each resource.

Table 1 – Average Annual Job Impacts by Resource per aMW (20-year annual average)

	Construction	O&M	Total
Solar PV (com/res)	8.7	5.8	14.4
Solar PV (utility)	4.2	3.2	7.3
Wind	0.9	1.1	1.9
EE	1.6	0.2	1.8
Natural Gas	0.8	0.5	1.3

Source: Synapse and NREL JEDI Model (industry spending patterns), IMPLAN (industry multipliers)

Figure 3 - Average Annual Job Impacts by Resource per aMW (20-year period)



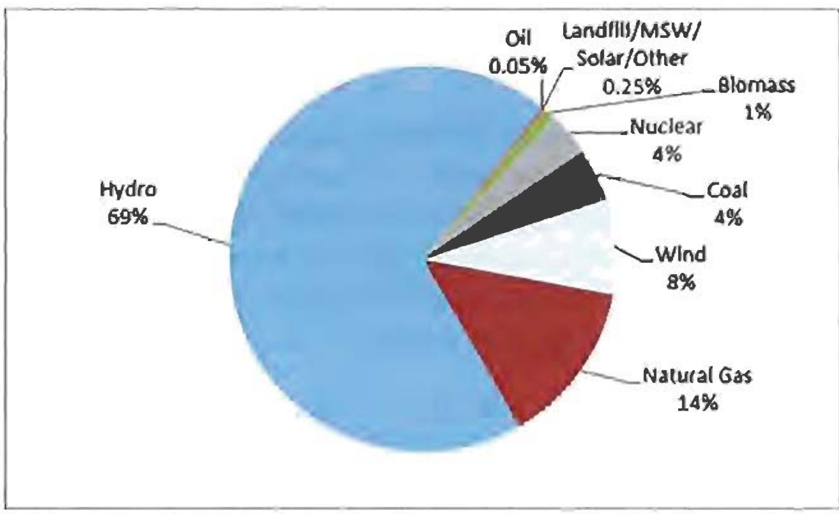
Source: Synapse and NREL JEDI Model (industry spending patterns), IMPLAN (industry multipliers)

2. EXISTING GENERATION AND ENERGY EFFICIENCY RESOURCES

2.1. Existing Generation Profile

The potential for Washington to replace out-of-state generation with its own resources will depend on support from state policies and the extent to which energy resources are readily available in the state. Washington currently has one of the cleanest energy portfolios of any state in the U.S. Nearly 70% of the state's generating capacity is hydropower (Figure 4). The state is the largest producer of hydropower and sixth largest producer of wind energy of any state in the U.S.[4] Washington will also upgrade hydropower and expand wind resources in the near future, in part, to comply with the its renewable energy goal of having 15% of energy come from new renewable sources by 2020.[5] Currently, only 4% of the state's in-state generating capacity is comprised of coal--from the Centralia plant--though this portion will soon be eliminated after that plant's retirement in 2025.

Figure 4 - Winter Generating Capacity by Resource (2011, % of total)



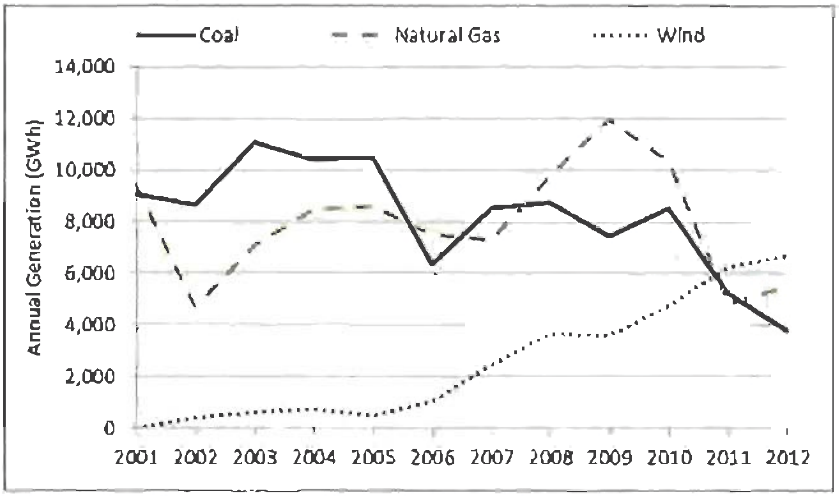
Source: Energy Information Administration

There has been a shift towards more renewable generation in Washington in recent years. As seen in Figure 5, wind generation has surpassed both coal and natural gas generation in the state in 2011 and 2012. There have been large fluctuations in natural gas and coal generation in Washington from year to year while wind has steadily increased as more turbines come on-line. The varying contributions of coal

[4] Energy Information Administration (EIA), Washington - State Profile and Energy Estimates.
[5] Washington Initiative 937:
http://www.dsireusa.org/incentives/incentive.cfm?Incentive_Code=WA15R&re=0&ee=0

and natural gas occur because these resources are subject to market energy and fuel prices, whereas wind is not.

Figure 5 - In-state Generation by Select Resources (2001-2012, GWh)



Source: Energy Information Administration

The state also offers plenty of room for growth in new renewable energy—especially for wind. The National Renewable Energy Laboratory (NREL) estimated the potential for wind generation in Washington to be over 18,000 MW of capacity, producing 55,550 GWh of energy (after excluding 70% of windy land that was unavailable for development).[6] Much of this supply comes from the central and southeastern parts of the state.[7] Solar generation has historically been low in the state but has potential to grow if the costs continue to decrease. According to the 2012 Washington State Energy Strategy:

> The eastern half of the state is richer in this resource than the western half, but even the relatively low rate of solar radiation energy in the Puget Sound region is sufficient to support residential rooftop photovoltaic systems, residential water heating systems and other solar technologies... Since the potential of the solar resource is so vast, a sufficiently low cost, new technology would alter the energy landscape significantly.[8]

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[6] National Renewable Energy Laboratory (NREL), 2011. Estimates of Windy Land Area and Wind Energy Potential by State

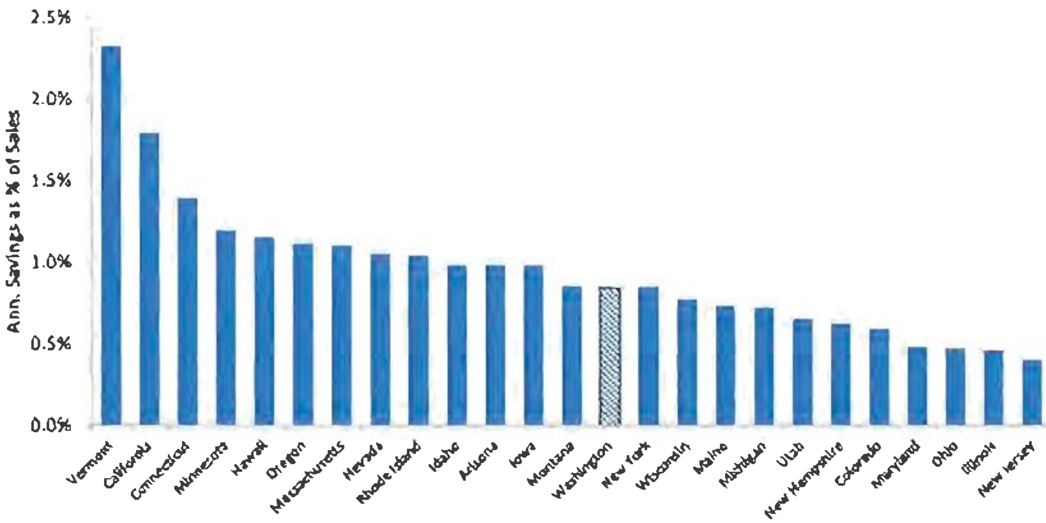
[7] Washington Department of Commerce (WA DOC), 2011. 2012 Washington State Energy Strategy with Forecasts 2012-2035: Issues and Analysis for the Washington State Legislature and Governor. December 2011. Found here: http://www.leg.wa.gov/documents/legislature/ReportsToTheLegislature/2012%20WSES_23140184-41ff-41d1-b551-4675573845db.pdf

[8] WA DOC, 2011.

2.2. Existing Energy Efficiency Programs and Savings

Washington is one of the leading states in the nation in promoting energy efficiency among consumers and businesses. ACEEE recently ranked Washington eighth among all states in energy efficiency; this ranking is based on ratepayer funded energy efficiency programs and policies, transportation policies, building energy codes, state government initiatives, and appliance efficiency standards.[9] Washington reduced retail sales by about 0.85% in 2010 through energy efficiency (Figure 6) and was ranked eighth among states in the nation by ACEEE in their 2012 State Energy Efficiency Scorecard.

Figure 6 - Incremental Energy Savings as Percent of Retail Sales in 2010 for Top 25 States



Source: ACEEE 2012

Washington enacted the Energy Independence Act (known as I-937) in 2006, part of which required all state electric utilities serving 25,000 or more customers to undertake all achievable cost-effective energy conservation.[10] In the two years following I-937, the affected utilities saved 263 aMW. The costs of these efficiency programs are typically low compared to the cost of supply side resources. We estimate the cost over the lifetime of energy savings could be 1 to 3 cents per kWh savings, based on recent program costs and savings achieved by Seattle City Light and Puget Sound Energy and assuming

[9] Foster, Ben et al. (ACEEE), 2012. The 2012 State Energy Efficiency Scorecard. Research Report E12C. October 3, 2012.

[10] Washington Initiative 937:
http://www.dsireusa.org/incentives/incentive.cfm?Incentive_Code=WA20R&re=0&ee=0

that these measures typically last about 10 years on average.[11] In contrast, the average retail electricity price for the state is about 7 cents per kWh.[12]

The majority of utilities in Washington and the surrounding states are receiving significant technical and financial support from two regional energy efficiency providers, the Northwest Energy Efficiency Alliance (NEEA) and Bonneville Power Administration (BPA). NEEA is a regional nonprofit entity dedicated solely to promoting energy efficiency through market transformation initiatives. NEEA's activities involve identifying promising technologies and ideas, and developing and testing operational approaches to promote these ideas in the market.[13] Examples of this process are NEEA's early activity to promote compact fluorescent lamps (CFL's),[14] and recent activity to promote ductless heat pumps.[15] BPA has been acquiring energy efficiency savings as defined by the Northwest Power and Conservation Council (NWPCC) for about 30 years. While BPA supports market transformation activities, the agency mainly focuses on efficiency acquisition through various programs for the roughly 135 public power entities to which they sell bulk power.

These active energy efficiency programs have a long history dating back to the late 1970's. The Northwest region has saved significant amounts of energy through utility conservation programs, state codes, federal appliance standards, and regional energy programs by the Northwest Energy Efficiency Alliance (NEEA). Among these policies, utility programs have had the largest impact. Through 2010, regional savings were approximately 4,500 average megawatts--more than enough to power all of the state of Idaho and Western Montana that year.[16] This level of energy savings represents a decrease of 19% in regional electricity sales in 2010.

In addition to these achievements, the Northwest and Washington State still have plenty of untapped energy efficiency potential. Table 2 summarizes the results of two recent energy efficiency potential studies in the region. One of the studies, conducted by Cadmus for Puget Sound Energy (PSE), found that PSE had a maximum achievable potential of 18% relative to projected energy sales in 2031.[17] (An achievable potential is a subset of an economic potential and takes into account various barriers to adopting energy efficiency measures.) Another study, shown in Table 2, was conducted by the NWPCC

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[11] Historical data were obtained from the Regional Technical Forum (RTF), available at http://rtf.nwcouncil.org/consreport/2011/

[12] U.S. EIA. "Sales and revenue data by state, monthly back to 1990 (Form EIA-826): http://www.eia.gov/electricity/data.cfm#sales

[13] Institute for Industrial Productivity, 2012. Energy Efficiency Resource Acquisition Program models in North America, p. 64 and 71

[14] Institute for Industrial Productivity, 2012.

[15] http://neea.org/initiatives/residential/ductless-heat-pumps

[16] NWPCC, 2010. 6th Power Plan Energy Efficiency Two-Pager: http://www.nwcouncil.org/energy/powerplan/6/2010-08/
Regional Technical Forum 2012-Progress Update 2011 Annual Report: http://rtf.nwcouncil.org/2011RTFAnnualReport.pdf

[17] Cadmus, 2011. Comprehensive Assessment of Demand-Side Resource Potentials (2012-2031). Prepared for Puget Sound Energy.

as part of their Sixth Power Plan in 2010. The NWPCC has found a large amount of energy efficiency potential, equaling about 23% of projected sales in the region in 2030. Much of the additional potential found in the NWPCC study is relevant to Washington (such as savings from the agricultural sector, utility distribution and consumer electronics, which were not incorporated the in the same way in the Cadmus study).

Table 2 - Comparison of Energy Efficiency Potential Estimates by Cadmus (for PSE) and NWPCC (% of Sector Demand) [18]

Sector	Cadmus	NWPCC
Residential	21%	29%*
Commercial	16%	17%*
Industrial	17%	15%
Agricultural		11%
Utility distribution**		2%
Total	18%	23%

Source: NWPCC 2011, Cadmus 2011.

** These numbers are rough approximations of potential that include savings from consumer electronics.*
*** Savings are compared to the total utility demand.*

Given Washington's historical performance on energy efficiency, the significant potential shown above and the continual support of efficiency measures through statewide policies–the state should continue to lead in this area in the future. Energy efficiency is the cheapest energy resource and, as the results from this report show, also a significant job-creator.

[18] NWPCC's estimates of achievable potential in 2029, screened at $100/MWh based on Table E-1 and Figure 4.8 of NWPCC (2010). Synapse estimated NWPCC's savings as % of forecasted load based on MWa potential data provided in the Plan and its sector-specific sales data for 2030 provided in Table 3-4 in the Plan.

3. Input Assumptions

This section presents the assumptions for renewable energy and energy efficiency costs used to develop the job impact results. These cost inputs include spending on:

- Construction of new natural gas, solar and wind facilities.
- Energy efficiency installations
- Operations and maintenance (O&M) of efficiency, natural gas, solar and wind facilities.

Synapse has developed customized spending patterns for each of the activities listed above and, along with the use of the IMPLAN model, developed job impacts specifically for Washington.

3.1. Natural Gas, Solar and Wind Generation Costs

Assumptions of capital, O&M costs and capacity factor for energy resources are presented in Table 3. These costs are assumed to take place in the near future (2015 to 2020).

- Natural gas capital and operating costs are also based on assumptions from the Energy Information Administration (EIA). The 51% capacity factor is based on the Pacific Northwest average assumed by the NWPCC.[19]
- Solar PV capital and operating costs are based on Synapse estimates from module price data, discussions with project developers and market data for utility-scale, commercial and residential rooftop projects. "Com/res" PV represents a mix of commercial and residential projects in western Washington, with an estimated cost of $4,000 per kW_{DC}. "Utility" PV represents utility-scale projects in eastern Washington--which have a higher capacity factor and a lower cost—has an estimated cost of $2,400 per kW_{DC}. The capacity factors for both types of projects were derived with NREL's PV Watts tool for Washington.[20]
- Wind capital and operating costs are based on Synapse estimates for projects in Class 4 wind regimes and assume an 80-meter hub height and 82.5-meter rotor diameter. Costs are based on data from NREL and Lawrence Berkeley Laboratories (LBL) and on analysis of recent power purchase agreements.[21,22] We use a capacity factor of 38%, considerably higher than historical wind capacity factors in

[19] NWPCC, 2013. Sixth Power Plan: Mid-Term Assessment Report. March 13, 2013.
[20] NREL PV Watts for Washington: http://rredc.nrel.gov/solar/calculators/pvwatts/version1/US/Washington/. The capacity factor was calculated using the DC capacity rating and AC energy produced.
[21] Wiser, Ryan et al., 2012. Recent Developments in the Levelized Cost of Energy from U.S. Wind Power Projects. National Renewable Energy Laboratory (NREL) and Lawrence Berkeley National Laboratory (LBNL).
[22] "Standard technology" is defined as 80 meter hub height and 82.5 meter rotor diameter and "low speed technology" is defined as 80 meter hub height and 100 meter rotor diameter.

Washington state, which are in the range of 30%.[23] Our capacity factor assumption is based on modeling of the wind technology being installed today. Our cost and capacity factor assumptions together produce levelized energy costs consistent with those seen in recent power purchase agreements.

Table 3 - Synapse Capital, O&M and Capacity Factor Cost Assumptions

Generation Type	Capital Cost in 2015 (2010$/kW)	Variable O&M (2010$/MWh)	Fixed O&M (2010$/kW)	Capacity Factor
Gas Combined Cycle	$1,100	$3.44	$14.5	51%
Solar PV (com/res)	$4,000	$0	$40	12%
Solar PV (utility)	$2,400	$0	$27.5	15%
Wind Land	$1,650	$0	$60	38%

Source: Synapse estimates based on EIA Annual Energy Outlook (AEO) 2011. Wiser 2012, NREL PV Watts (capital and O&M costs), and select natural gas generation.

3.2. Energy Efficiency Installation Costs

Synapse developed cost estimates for energy efficiency in Washington based on a review of current programs offered by state utilities and on previous research of efficiency measure spending in other states. Typically, energy efficiency program spending is reported at a sector or program level as well as for specific administrative tasks such as planning, marketing, evaluation, measurement and verification (EM&V). Because detailed measure-level data was not available for Washington, Synapse relied on measure level cost data from key utilities in Minnesota and Massachusetts which were selected because they offered data relevance and availability, existence of large energy savings, high program spending, and cold or temperate climates (ensuring that the types of measures would be comparable). Xcel Energy in Minnesota and NSTAR Electric in Massachusetts were selected because they had dominant electric energy efficiency programs in their respective states.[24] In order to generate Washington-specific data, Synapse performed the following additional steps:

1) We developed annual energy efficiency program savings and spending by sector based on recent historical program data for Puget Sound Energy and Seattle City Light, using data from the Regional Technical Forum.[25]

[23] Based on historical generation at Wild Horse, Hopkins Ridge and Big Horn wind farms.

[24] Xcel Energy. 2011. Status Report & Associated Compliance Filings Minnesota Electric and Natural Gas Conservation Improvement Program Docket No. E, G002/CIP-09-198, http://www.xcelenergy.com/staticfiles/xe/Regulatory/Regulatory%20PDFs/MN-DSM-CIP-2011-Status-Report.pdf; and NSTAR Electric Company. 2012. 2013-2015 Three-Year Energy Efficiency Plan, D.P.U. 12-110, Exh. 5, November 2012.

[25] The Regional Technical Forum is an advisory committee in the Northwest to develop standards to verify and evaluate energy conservation savings.

2) These program costs were then used to derive the total costs by sector (residential, commercial and industrial) for the state based on the mix of Xcel Minnesota program spending.

3) Synapse then developed material cost coefficients (as % of total efficiency investment) by allocating the estimate of Washington's total costs over each relevant program type and industry (for use in the IMPLAN model) based on the end-use data from Xcel Minnesota (e.g., lighting bulbs, appliances, and HVAC equipment for Home Performance with ENERGY STAR program).

4) We then adjusted these material cost coefficients by incorporating measure profiles from Nstar Massachusetts, comparing the incremental measure cost data as % of total "measure" cost available from Nstar with the incremental measure data we developed for Washington based on Xcel MN data. We have also reviewed administration and marketing spending data for Puget Sound Energy to develop Washington-specific cost coefficients for these sectors.

A summary of the costs of materials and the program administrative costs for efficiency measures is presented in Table 4 with each relevant IMPLAN industry. These costs accounted for 69% of the total energy efficiency investment spending. The rest of the spending was treated as labor spending, which represents payments to contractors to install the efficiency measures.

Table 4 - Washington Energy Efficiency Non-Labor Coefficient Vectors

	IMPLAN industry	%
3104	Wood pulp	2%
3216	Air conditioning, refrigeration, and warm air heating equipment	16%
3259	Electric lamp bulbs and parts	27%
3261	Small electrical appliances	0.1%
3263	Household refrigerators and home freezers	0.4%
3265	Other major household appliances	0.4%
3416	Electronic and precision equipment repairs and maintenance	2%
3417	Commercial and industrial machinery and equipment repairs and maintenance	3%
3230	Other general purpose machinery	10%
3031	Electricity, and distribution services	3%
3377	Advertising and related services	4%
Total Materials		**69%**
Total Labor		**31%**

Source: Xcel Minnesota (MN Program Spending), Regional Technical Forum 2012 - Progress Update 2011 Annual Report (WA Annual Spending), Synapse estimate of WA Program spending

Finally, our review of the recent program savings and estimates of program spending by PSE and City of Seattle found that the average program cost in Washington is $0.22 per first year kWh saved (Table 5). Based on our analysis of estimated program and measure costs for Washington, we estimated that the program costs accounts for 46% of the total energy efficiency investment—the rest of the spending is paid out-of-pocket by participants. Applying this factor to the $0.22 per kWh program cost, we estimated the total efficiency investment cost for Washington to be $0.48 per kWh first year saved. However, little spending is needed in order to keep an efficiency measure operating once it has been installed, as opposed to generation resources which require frequent maintenance.

Table 5 - Annual Average Program Spending, Savings, and Cost of Saved Energy for PSE and City of Seattle[26]

Sector	WA Program Annual Average Spending	Savings (kWh)	$ per first year kWh saved
Residential	**$34,517,497**	**197,023,241**	**$0.18**
Low-Income	$2,434,815	2,295,630	$1.06
Commercial & Industrial	**$45,524,454**	**176,187,763**	**$0.26**
Others	$7,237,939	35,931,003	$0.20
Total Program Costs	**$89,714,704**	**411,437,636**	**$0.22**
Total Investment Costs			***$0.48***

Source: Regional Technical Forum 2012 - Progress Update 2011 Annual Report (WA Annual Spending), Synapse estimate of $ per kWh saved based on savings and spending from 2008 to 2010.

[26] The data is available at http://rtf.nwcouncil.org/consreport/2011/

4. Employment Impact Methodology

The costs discussed in this section provide the inputs for the employment impact factor analysis. In general, economic impacts are a measure of an investment or policy's stimulus (or footprint) on a local economy. They are composed of direct, indirect and induced impacts, described below:

- **Direct impacts** include contractors and workers during the construction period or that operate and maintain the generating facilities while they are up and running. Synapse first estimated the materials versus labor spending for each resource. The amount of labor spending for each resource divided by the associated industry wages in Washington results in the number of direct jobs.
- **Indirect impacts** include jobs associated with materials to support construction, operations and maintenance (e.g. wind farms purchase turbines from manufacturers). The extent to which these materials are produced in-state (e.g. the portion of wind turbines that are manufactured in Washington) is an important determinant of indirect impacts. Synapse relied on the IMPLAN model's estimates for the portion of each industry's demand that is met by in-state suppliers. Synapse has also improved on the standard IMPLAN assumptions for the electricity industry by using NREL's JEDI (Jobs and Economic Development Impacts model) to develop customized spending patterns for each technology.
- **Induced impacts** include jobs for goods and services that serve households. These occur when workers from both the direct and indirect activities re-spend their wages, further stimulating the local economy. This analysis does not include the re-spending of energy savings by energy efficiency participants.

The direct job impacts are estimated based on the share of spending on labor for each resource. The share that is dedicated to labor is then divided by the average wage for that sector to estimate the direct jobs. Table 6 shows the wage assumptions used for each resource. The O&M wages are the U.S. average taken from NREL's JEDI models for each resource type. These wages were then adjusted to be Washington-specific by taking the average wage in the IMPLAN "electric power generation, transmission, and distribution" industry from Washington relative to the U.S. and applying that factor to the individual salaries from NREL's JEDI models.[27] Construction wages were based on the "construction of other new nonresidential structures" IMPLAN industry in Washington and were not differentiated by resource. Labor spending is run through the IMPLAN model using the "labor income" vector which captures how income is typically re-spent—this produces "induced" impacts.[28]

[27] According to the 2011 IMPLAN model, the average wage in the Washington electric power generation, transmission, and distribution industry is 89% of the U.S average wage.
[28] These wages are an industry-wide average so represent a mix of union and non-union labor.

Table 6 – Worker Wage Assumptions for Direct Jobs by Resource

Generation Type	O&M	Construction
Natural Gas CC	$62,000	$62,000
Solar PV	$67,000	$62,000
Wind Land	$58,000	$62,000
Energy Efficiency	N/A	$62,000

Source: Synopse, NREL JEDI Model, and IMPLAN

Indirect impacts are generated by the spending on materials for construction and O&M that are produced in-state. This spending is allocated based on the composition of supplies needed by each resource type as developed by Synapse using the JEDI model and IMPLAN. The vector of materials spending is run through the IMPLAN model for each resource, generating "indirect" impacts for suppliers of the materials and their suppliers, etc.

The IMPLAN modeling for both labor and materials results in job impacts per amount of investment for each energy resource in Washington—shown in Tables 7 and 8. These include the direct, indirect, and induced jobs per million spent on construction, efficiency installations, O&M and fuel. In general, the more labor-intensive activities will provide the most jobs per investment dollar spent—particularly for solar PV and EE installations which consist mostly of small projects. Solar PV and wind O&M both have notably higher jobs per dollar spent compared to coal and natural gas since a higher share of O&M spending is dedicated to labor--22% for wind and 55% for solar PV compared to 6% for coal and 1% for natural gas. This is due, in part, to the fact that much of fossil fuel generation spending consists of fuel that is produced out-of-state rather than on materials and labor provided in-state.

Table 7 – Construction and Installation - Direct, Indirect and Induced Job Impacts per Million Dollars in Spending

Generation Type	Direct	Indirect & Induced	Total Construction/ Installation Impacts
Natural Gas CC	1.8	5.3	7.1
Solar PV	0.8	4.1	4.9
Wind Land	1.1	2.6	3.7
Energy Efficiency	5.6	3.2	8.8

Source: Synopse and NREL JEDI Model (industry spending patterns), IMPLAN (industry multipliers)

Table 8 – Operations and Maintenance - Direct, Indirect and Induced Job Impacts per Million Dollars in Spending

Generation Type	Direct	Indirect & Induced	Total O&M Impacts
Natural Gas CC	0.2	1.4	1.6
Solar PV	9.5	7.0	16.5
Wind Land	3.3	3.2	6.5
Energy Efficiency	4.1	5.5	9.6

Source: Synapse and NREL JEDI Model (industry spending patterns), IMPLAN (industry multipliers)

The spending per average megawatt is derived from the costs of generation and capacity factors (presented in Table 3) and the estimated total investment cost of energy efficiency in Washington (presented in Table 5). The spending per aMW for construction and efficiency installation was estimated by dividing the total cost by first year generation or efficiency savings, respectively. Wind is the cheapest generation resource to operate per aMW. Energy efficiency installation costs per aMW of annual savings are close to that of natural gas CC and wind for annual generation; however, unlike generation, efficiency resources have very little O&M costs. The administrative and marketing activities associated with efficiency were taken form part of the installation costs and spread over a 20-year period.

Table 9 – Capital and O&M/Fuel Spending per Annual Generation/Savings per Average Megawatt

Generation Type	Construction/ EE Installation	O&M and Fuel
Natural Gas CC	$2.27	$0.31
Solar PV (com/res)	$35.10	$0.35
Solar PV (utility)	$16.85	$0.19
Wind Land	$4.57	$0.17
Energy Efficiency	$3.78	$0.02

Source: Synapse and NREL JEDI Model (industry spending patterns), IMPLAN (industry multipliers)

Finally, Tables 10 and 11 show the job impacts per average megawatt, which were calculated by multiplying the results from Tables 7 and 8 with factors in Table 9. This measure offers a better comparison between resources than jobs per megawatt since it accounts for how often each resource operates (on average) throughout the year.

Table 10 shows the impact from short-term activities of building new generating capacity and installing energy efficiency measures. Solar photovoltaic (PV) has the largest impact per aMW by far with 173 job-years for commercial and residential projects and 83 job-years for utility-scale projects—the latter is smaller due to economies of scale when installing large projects. The large impacts from solar PV come as a result of the labor-intensity of these installations. The utility-scale solar projects were assumed to be located in eastern Washington which has better solar resource than in the western part of the state. Energy efficiency installation--another labor-intensive activity--generates the next highest factor with an estimated 32 total job-years per aMW saved. Wind construction generates slightly more activity than natural gas—17 job-years per aMW compared to 16, respectively.

Table 11 shows the job impacts per average megawatt for O&M and fuel. These represent the impact from long-term activities needed to run generating facilities each year. Again, solar PV has the largest impact of any resource with 5.8 jobs per aMW for residential and commercial projects and 3.2 jobs per aMW for utility-scale projects. Wind generation generates more O&M activity than natural gas in the state—1.1 to 0.5 jobs per aMW, respectively. Wind power involves more labor-intensive O&M activities and, unlike natural gas, requires no fuel spending (which would mostly leave the state).

Table 10 – Construction and Installation - Direct, Indirect and Induced Job Impacts per Average Megawatt

Generation Type	Direct	Indirect & Induced	Total Construction/ Installation Impacts
Natural Gas CC	4	12	**16**
Solar PV (com/res)	28	145	**173**
Solar PV (utility)	14	70	**83**
Wind Land	5	12	**17**
Energy Efficiency	24	8	**32**

Source: Synapse and NREL JEDI Model (industry spending patterns), IMPLAN (industry multipliers. Coal construction impacts were excluded since there are no new coal plants proposed in Washington.

Table 11 – Operations and Maintenance - Direct, Indirect and Induced Job Impacts per Average Megawatt

Generation Type	Direct	Indirect & Induced	Total O&M Impacts
Natural Gas CC	0.1	0.4	**0.5**
Solar PV (com/res)	3.3	2.5	**5.8**
Solar PV (utility)	1.8	1.4	**3.2**
Wind Land	0.6	0.5	**1.1**
Energy Efficiency	0.1	0.1	**0.2**

Source: Synapse and NREL JEDI Model (industry spending patterns), IMPLAN (industry multipliers)

5. CONCLUSION

Investment in new natural gas, wind, solar, or EE will result in net new jobs in Washington. However, new solar PV, wind and EE create more jobs than natural gas generation per unit of energy used in the state, on average. The annual average job impacts per aMW over a 20-year period, when combining construction and O&M activities, show that small and large-scale solar PV have the largest impact of the energy resources. The difference in impacts between small and large-scale PV installations is largely due to economies of scale—less labor is required and panels are cheaper for large-scale projects, per aMW. Wind generation and energy efficiency installations create impacts of 1.9 and 1.8 average annual jobs per aMW, respectively. Natural gas generation creates 1.3 average annual jobs per aMW.

A state energy portfolio should not be based on these results alone--solar PV creates the most jobs per aMW but cannot fully replace lost generation from coal on its own. However, this analysis can be used to estimate the job impacts the state could expect from a cleaner energy portfolio once one is chosen. Washington State has already made considerable progress in developing energy efficiency and renewable energy (especially hydropower and wind). This study shows that expanding clean energy activity further in the state will bear significant fruit in the form of new job activity.

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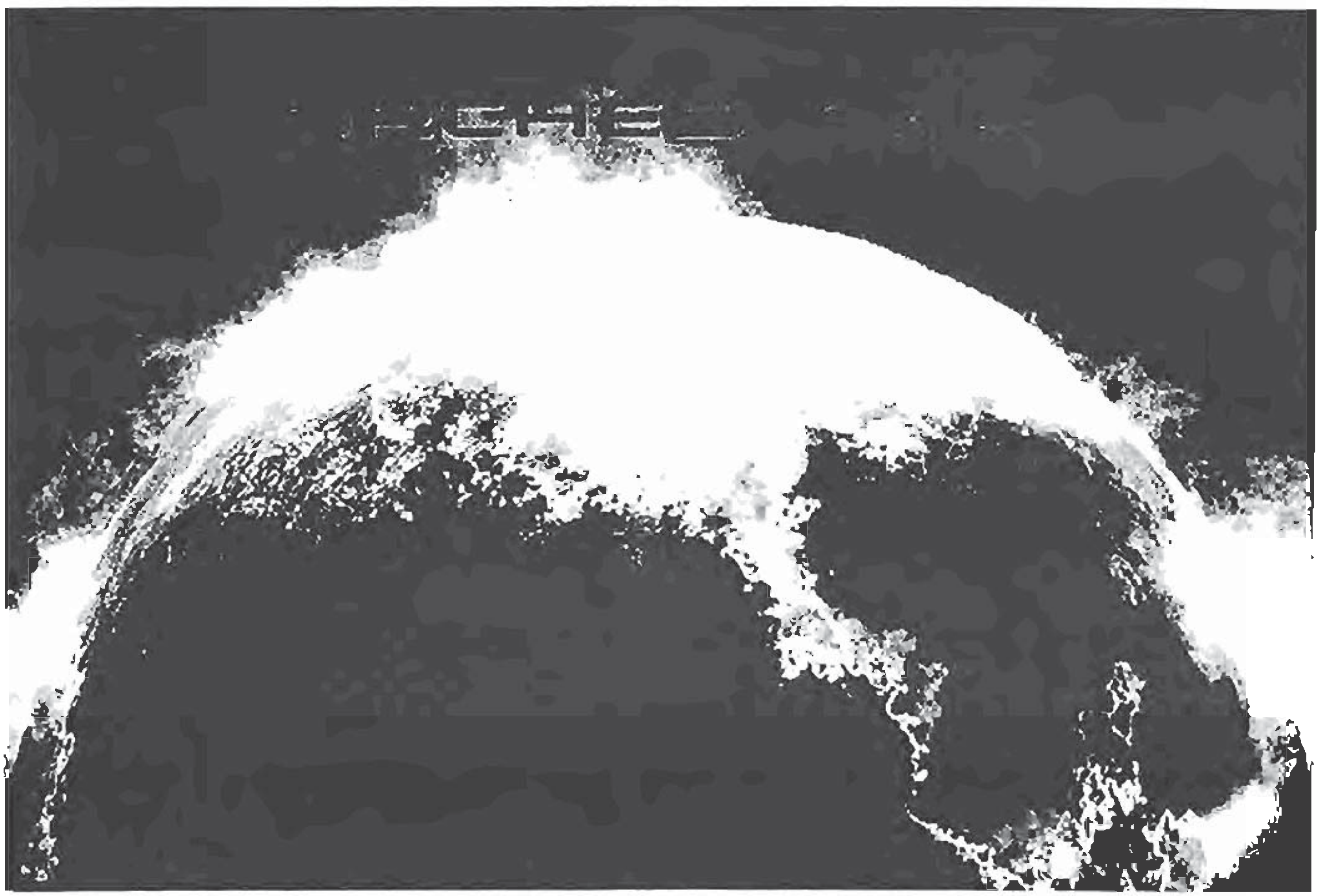
Hansen Study: Climate Sensitivity Is High, Burning All Fossil Fuels Would Make Most Of Planet 'Uninhabitable'

BY JOE ROMM ON SEPTEMBER 17, 2013 AT 3:46 PM



James Hansen, the country's most prescient climatologist, is out with another must-read paper,

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

Climate sensitivity, sea level and atmospheric carbon dioxide

Abstract

Cenozoic temperature, sea level and CO_2 covariations provide insights into climate sensitivity to external forcings and sea-level sensitivity to climate change. Climate sensitivity depends on the initial climate state, but potentially can be accurately inferred from precise palaeoclimate data. Pleistocene climate oscillations yield a fast-feedback climate sensitivity of 3±1°C for a 4 W m^{-2} CO_2 forcing if Holocene warming relative to the Last Glacial Maximum (LGM) is used as calibration, but the error (uncertainty) is substantial and partly subjective because of poorly defined LGM global temperature and possible human influences in the Holocene. Glacial-to-interglacial climate change leading to the prior (Eemian) interglacial is less ambiguous and implies a sensitivity in the upper part of the above range, i.e. 3–4°C for a 4 W m^{-2} CO_2 forcing. Slow feedbacks, especially change of ice sheet size and atmospheric CO_2, amplify the total Earth system sensitivity by an amount that depends on the time scale considered. Ice sheet response time is poorly defined, but we show that the slow response and hysteresis in prevailing ice sheet models are exaggerated. We use a global model, simplified to essential processes, to investigate state dependence of climate sensitivity, finding an increased sensitivity towards warmer climates, as low cloud cover is diminished and increased water vapour elevates the tropopause. Burning all fossil fuels, we conclude, would make most of the planet uninhabitable by humans, thus calling into question strategies that emphasize adaptation to climate change.

climate   climate sensitivity   palaeoclimate   sea level

1. Introduction

Humanity is now the dominant force driving changes in the Earth's atmospheric composition and climate [1]. The largest climate forcing today, i.e. the greatest imposed perturbation of the planet's energy balance [1 , 2], is the human-made increase in atmospheric greenhouse gases (GHGs), especially CO_2 from the burning of fossil fuels.

Earth's response to climate forcings is slowed by the inertia of the global ocean and the great ice sheets on Greenland and Antarctica, which require centuries, millennia or longer to approach their full response to a climate forcing. This long response time makes the task of avoiding dangerous human alteration of climate particularly difficult, because the human-made climate forcing is being imposed rapidly, with most of the current forcing having been added in just the past several decades. Thus, observed climate changes are only a partial response to the current climate forcing, with further response still 'in the pipeline' [3].

Climate models, numerical climate simulations, provide one way to estimate the climate response to forcings, but it is difficult to include realistically all real-world processes. Earth's palaeoclimate history allows empirical assessment of climate sensitivity, but the data have large uncertainties. These approaches are usually not fully independent, and the most realistic eventual assessments will be ones combining their greatest strengths.

We use the rich climate history of the Cenozoic era in the oxygen isotope record of ocean sediments to explore the relation of climate change with sea level and atmospheric CO_2, inferring climate sensitivity empirically. We use isotope data from Zachos *et al.* [4], which are improved over data used in our earlier study [5], and we improve our prescription for separating the effects of deep ocean temperature and ice volume in the oxygen isotope record as well as our prescription for relating deep ocean temperature to surface air temperature. Finally, we use an efficient climate model to expand our estimated climate sensitivities beyond the Cenozoic climate range to snowball Earth and runaway greenhouse conditions.

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2. Overview of Cenozoic climate and our analysis approach

The Cenozoic era, the past 65.5 million years (Myr), provides a valuable perspective on climate [5 , 6] and sea-level change [7], and Cenozoic data help clarify our analysis approach. The principal dataset we use is the temporal variation of the oxygen isotope ratio ($\delta^{18}O$ relative to $\delta^{16}O$; figure 1*a* right-hand scale) in the shells of deep-ocean-dwelling microscopic shelled animals (foraminifera) in a near-global compilation of ocean sediment cores [4]. $\delta^{18}O$ yields an estimate of the deep ocean temperature (figure 1*b*), as discussed in §3. Note that coarse temporal resolution of $\delta^{18}O$ data in the intervals 7–17, 35–42 and 44–65 Myr reduces the apparent amplitude of glacial–interglacial climate fluctuations (see electronic supplementary material, figure S1). We use additional proxy measures of climate change to supplement the $\delta^{18}O$ data in our quantitative analyses.

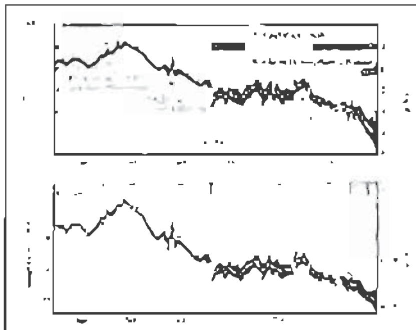

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Figure 1.

(*a*) Global deep ocean $\delta^{18}O$ from Zachos *et al.* [4] and (*b*) estimated deep ocean temperature based on the prescription in our present paper. Black data points are five-point running means of the original temporal resolution; red and blue curves have a 500 kyr resolution. Coarse temporal sampling reduces the amplitude of glacial–interglacial oscillations in the intervals 7–17, 35–42 and 44–65 Myr BP.

Carbon dioxide is involved in climate change throughout the Cenozoic era, both as a climate forcing and as a climate feedback. Long-term Cenozoic temperature trends, the warming up to about 50 Myr before present (BP) and subsequent long-term cooling, are likely to be, at least in large part, a result of the changing natural source of atmospheric CO_2, which is volcanic emissions that occur mainly at continental margins due to plate tectonics (popularly 'continental drift'); tectonic activity also affects the weathering sink for CO_2 by exposing fresh rock. The CO_2 tectonic source grew from 60 to 50 Myr BP as India subducted carbonate-rich ocean crust while moving through the present Indian Ocean prior to its collision with Asia about 50 Myr BP [8], causing atmospheric CO_2 to reach levels of the order of 1000 ppm at 50 Myr BP [9]. Since then, atmospheric CO_2 declined as the Indian and Atlantic Oceans have been major depocentres for carbonate and organic sediments while subduction of carbonate-rich crust has been limited mainly to small regions near Indonesia and Central America [10], thus allowing CO_2 to decline to levels as low as 170 ppm during recent glacial periods [11]. A climate forcing due to a CO_2 change from 1000 to 170 ppm is more than 10 W m^{-2}, which compares with forcings of the order of 1 W m^{-2} for competing climate forcings during the Cenozoic era [5], specifically long-term change of solar irradiance and change of planetary albedo (reflectance) owing to the overall minor displacement of continents in that era.

Superimposed on the long-term trends are occasional global warming spikes, 'hyperthermals', most prominently the Palaeocene–Eocene Thermal Maximum (PETM) at approximately 56 Myr BP [12] and the Mid-Eocene Climatic Optimum at approximately 42 Myr BP [13], coincident with large temporary increases of atmospheric CO_2. The most studied hyperthermal, the PETM, caused global warming of at least 5°C coincident with injection of a likely 4000–7000 Gt of isotopically light carbon into the atmosphere and ocean [14]. The size of the carbon injection is estimated from changes in the stable carbon isotope ratio $^{13}C/^{12}C$ in sediments and from ocean acidification implied by changes in the ocean depth below which carbonate dissolution occurred.

The potential carbon source for hyperthermal warming that received most initial attention was methane hydrates on continental shelves, which could be destabilized by sea floor warming [15]. Alternative sources include release of carbon from Antarctic permafrost and peat [16]. Regardless of the carbon source(s), it has been shown that the hyperthermals were astronomically paced, spurred by coincident maxima in the Earth's orbit eccentricity and spin axis tilt [17], which increased high-latitude insolation and warming. The PETM was followed by successively weaker astronomically paced hyperthermals, suggesting that the carbon source(s) partially recharged in the interim [18]. A high temporal resolution sediment core from the New Jersey continental shelf [19] reveals that PETM warming in at least that region began about 3000 years prior to a massive release of isotopically light carbon. This lag and climate simulations [20] that produce large warming at intermediate ocean depths in response to initial surface warming are consistent with the concept of a methane hydrate role in hyperthermal events.

The hyperthermals confirm understanding about the long recovery time of the Earth's carbon cycle [21] and reveal the potential for threshold or 'tipping point' behaviour with large amplifying climate feedback in response to warming [22]. One implication is that if humans burn most of the fossil fuels, thus injecting into the atmosphere an amount of CO_2 at least comparable to that injected during the PETM, the CO_2 would stay in the surface carbon reservoirs (atmosphere, ocean, soil, biosphere) for tens of thousands of years, long enough for the atmosphere, ocean and ice sheets to fully respond to the changed atmospheric composition. In addition, there is the potential that global warming from fossil fuel CO_2 could spur release of CH_4 and CO_2 from methane hydrates or permafrost. Carbon release during the hyperthermals required several thousand years, but that long injection time may have been a function of the pace of the astronomical forcing, which is much slower than the pace of fossil fuel burning.

The Cenozoic record also reveals the amplification of climate change that occurs with growth or decay of ice sheets, as is apparent at about 34 MyrBP when the Earth became cool enough for large-scale glaciation of Antarctica and in the most recent 3–5 Myr with the growth of Northern Hemisphere ice sheets. Global climate fluctuated in the 20 Myr following Antarctic glaciation with warmth during the Mid-Miocene Climatic Optimum (MMCO, 15 Myr BP) possibly comparable to that at 34 MyrBP, as, for example, Germany became warm enough to harbour snakes and crocodiles that require an annual temperature of about 20°C or higher and a winter temperature more than 10°C [23]. Antarctic vegetation in the MMCO implies a summer temperature of approximately 11°C warmer than today [24] and annual sea surface temperatures ranging from 0°C to 11.5°C [25].

Superimposed on the long-term trends, in addition to occasional hyperthermals, are continual high-frequency temperature oscillations, which are apparent in figure 1 after 34 MyrBP, when the Earth became cold enough for a large ice sheet to form on Antarctica, and are still more prominent during ice sheet growth in the Northern Hemisphere. These climate oscillations have dominant periodicities, ranging from about 20 to 400 kyr, that coincide with variations in the Earth's orbital elements [26], specifically the tilt of the Earth's spin axis, the eccentricity of the orbit and the time of year when the Earth is closest to the Sun. The slowly changing orbit and tilt of the spin axis affect the seasonal distribution of insolation [27], and thus the growth and decay of ice sheets, as proposed by Milankovitch [28]. Atmospheric CO_2, CH_4 and N_2O have varied almost synchronously with global temperature during the past 800 000 years for which precise data are available from ice cores, the GHGs providing an amplifying feedback that magnifies the climate change instigated by orbit perturbations [29 – 31].

Ocean and atmosphere dynamical effects have been suggested as possible causes of some climate change within the Cenozoic era; for example, topographical effects of mountain building [32], closing of the Panama Seaway [33] or opening of the Drake Passage [34]. Climate modelling studies with orographic changes confirm significant effects on monsoons and on Eurasian temperature [35]. Modelling studies indicate that closing of the Panama Seaway results in a more intense Atlantic thermohaline circulation, but only small effects on Northern Hemisphere ice sheets [36]. Opening of the Drake Passage surely affected ocean circulation around Antarctica, but efforts to find a significant effect on global temperature have relied on speculation about possible effects on atmospheric CO_2 [37]. Overall, there is no strong evidence that dynamical effects are a major direct contributor to Cenozoic global temperature change.

We hypothesize that the global climate variations of the Cenozoic (figure 1) can be understood and analysed via slow temporal changes in Earth's energy balance, which is a function of solar irradiance, atmospheric composition (specifically long-lived GHGs) and planetary surface albedo. Using measured amounts of GHGs during the past 800000 years of glacial–interglacial climate oscillations and surface albedo inferred from sea-level data, we show that a single empirical 'fast-feedback' climate sensitivity can account well for the global temperature change over that range of climate states. It is certain that over a large climate range climate sensitivity must become a strong function of the climate state, and thus we use a simplified climate model to investigate the dependence of climate sensitivity on the climate state. Finally, we use our estimated state-dependent climate sensitivity to infer Cenozoic CO_2 change and compare this with proxy CO_2 data, focusing on the Eocene climatic optimum, the Oligocene glaciation, the Miocene optimum and the Pliocene.

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3. Deep ocean temperature and sea level in the Cenozoic era

The $\delta^{18}O$ stable isotope ratio was the first palaeothermometer, proposed by Urey [38] and developed especially by Emiliani [39]. There are now several alternative proxy measures of ancient climate change, but the $\delta^{18}O$ data (figure 1*a*) of Zachos *et al.* [4], a conglomerate of the global ocean sediment cores, is well suited for our purpose as it covers the Cenozoic era with good temporal resolution. There are large, even dominant, non-climatic causes of $\delta^{18}O$ changes over hundreds of millions of years [40], but non-climatic change may be small in the past few hundred million years [41] and is generally neglected in Cenozoic climate studies. The principal difficulty in using the $\delta^{18}O$ record to estimate global deep ocean temperature, in the absence of non-climatic change, is that $\delta^{18}O$ is affected by the global ice mass as well as the deep ocean temperature.

We make a simple estimate of global sea-level change for the Cenozoic era using the near-global $\delta^{18}O$ compilation of Zachos *et al.* [4]. More elaborate and accurate approaches, including use of models, will surely be devised, but comparison of our result with other approaches is instructive regarding basic issues such as the vulnerability of today's ice sheets to near-term global warming and the magnitude of hysteresis effects in ice sheet growth and decay.

During the Early Cenozoic, between 65.5 and 35 Myr BP, the Earth was so warm that there was little ice on the planet and the deep ocean temperature is approximated by [6]

$$T_{do}\ (^{\circ}C) = -4\delta^{18}O + 12 \quad (\text{for } \delta^{18}O < 1.75). \tag{3.1}$$

Hansen *et al.* [5] made the approximation that, as the Earth became colder and continental ice sheets grew, further increase in $\delta^{18}O$ was due, in equal parts, to deep ocean temperature change and ice mass change,

$$T_{do}\ (^{\circ}C) = -2(\delta^{18}O - 4.25) \quad (\text{for } \delta^{18}O > 1.75). \tag{3.2}$$

Equal division of the $\delta^{18}O$ change into temperature change and ice volume change was suggested by comparing $\delta^{18}O$ at the endpoints of the climate change from the nearly ice-free planet at 35 Myr BP (when $\delta^{18}O$ approx. 1.75) with the Last Glacial Maximum

(LGM), which peaked approximately 20 kyr BP. The change of $\delta^{18}O$ between these two extreme climate states (approx. 3) is twice the change of $\delta^{18}O$ due to temperature change alone (approx. 1.5), with the temperature change based on the linear relation (??eq3.1) and estimates of T_{do}~5°C at 35 Myr BP (figure 1) and approximately −1°C at the LGM [42]. This approximation can easily be made more realistic. Although ice volume and deep ocean temperature changes contributed comparable amounts to $\delta^{18}O$ change on average over the full range from 35 Myr to 20 kyr BP, the temperature change portion of the $\delta^{18}O$ change must decrease as the deep ocean temperature approaches the freezing point [43]. The rapid increase in $\delta^{18}O$ in the past few million years was associated with the appearance of Northern Hemisphere ice sheets, symbolized by the dark blue bar in figure 1*a*.

The sea-level change between the LGM and Holocene was approximately 120 m [44 , 45]. Thus, two-thirds of the 180 m sea-level change between the ice-free planet and the LGM occurred with formation of Northern Hemisphere ice (and probably some increased volume of Antarctic ice). Thus, rather than taking the 180 m sea-level change between the nearly ice-free planet of 34 Myr BP and the LGM as being linear over the entire range (with 90 m for $\delta^{18}O<3.25$ and 90 m for $\delta^{18}O>3.25$), it is more realistic to assign 60 m of sea-level change to $\delta^{18}O$ 1.75–3.25 and 120 m to $\delta^{18}O>3.25$. The total deep ocean temperature change of 6°C for the change of $\delta^{18}O$ from 1.75 to 4.75 is then divided two-thirds (4°C) for the $\delta^{18}O$ range 1.75–3.25 and 2°C for the $\delta^{18}O$ range 3.25–4.75. Algebraically,

$$SL\,(m) = 60 - 40(\delta^{18}O - 1.75) \quad (\text{for } \delta^{18}O < 3.25),$$ 3.3

$$SL\,(m) = -120\frac{\delta^{18}O - 3.25}{1.65} \quad (\text{for } \delta^{18}O > 3.25),$$ 3.4

$$T_{do}\,(°C) = 5 - 8\frac{\delta^{18}O - 1.75}{3} \quad (\text{for } \delta^{18}O < 3.25)$$ 3.5

and

$$T_{do}\,(°C) = 1 - 4.4\frac{\delta^{18}O - 3.25}{3} \quad (\text{for } \delta^{18}O > 3.25),$$ 3.6

where SL is the sea level and its zero point is the Late Holocene level. The coefficients in equations (3.4) and (3.6) account for the fact that the mean LGM value of $\delta^{18}O$ is approximately 4.9. The resulting deep ocean temperature is shown in figure 1*b* for the full Cenozoic era.

Sea level from equations (3.3) and (3.4) is shown by the blue curves in figure 2, including comparison (figure 2*c*) with the Late Pleistocene sea-level record of Rohling *et al.* [47], which is based on analysis of Red Sea sediments, and comparison (figure 2*b*) with the sea-level chronology of de Boer *et al.* [46], which is based on ice sheet modelling with the $\delta^{18}O$ data of Zachos *et al.* [4] as a principal input driving the ice sheet model. Comparison of our result with that of de Boer *et al.* [46] for the other periods of figure 2 is included in the electronic supplementary material, where we also make available our numerical data. Deep ocean temperature from equations (3.5) and (3.6) is shown for the Pliocene and Pleistocene in figure 3 and for the entire Cenozoic era in figure 1.

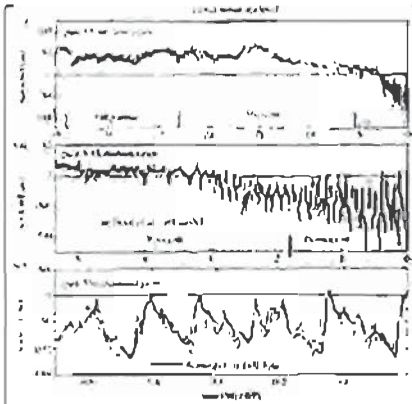

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Figure 2.

(*a–c*) Sea level from equations (3.3) and (3.4) using $\delta^{18}O$ data of Zachos *et al.* [4], compared in (*b*) with ice sheet model results of de Boer *et al.* [46] and in (*c*) with the sea-level analysis of Rohling *et al.* [47].

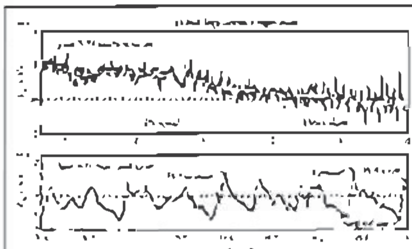

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Figure 3.

Deep ocean temperature in (*a*) the Pliocene and Pleistocene and (*b*) the last 800 000 years. High-frequency variations (black) are five-point running means of the original data [4], whereas the blue curve has a 500 kyr resolution. The deep ocean temperature for the entire Cenozoic era is in figure 1*b*.

Differences between our inferred sea-level chronology and that from the ice sheet model [46] are relevant to the assessment of the potential danger to humanity from future sea-level rise. Our estimated sea levels have reached +5 to 10 m above the present sea level during recent interglacial periods that were barely warmer than the Holocene, whereas the ice sheet model yields maxima at most approximately 1 m above the current sea level. We find the Pliocene sea level varying between about +20 m and −50 m, with the Early Pliocene averaging about +15 m; the ice sheet model has a less variable sea level with the Early Pliocene averaging about +8 m. A 15 m sea-level rise implies that the East Antarctic ice sheet as well as West Antarctica and Greenland ice were unstable at a global temperature no higher than those projected to occur this century [1 , 48].

How can we interpret these differences, and what is the merit of our simple $\delta^{18}O$ scaling? Ice sheet models constrained by multiple observations may eventually provide our best estimate of sea-level change, but as yet models are primitive. Hansen [49 , 50] argues that real ice sheets are more responsive to climate change than is found in most ice sheet models. Our simple scaling approximation implicitly assumes that ice sheets are sufficiently responsive to climate change that hysteresis is not a dominant effect; in other words, ice volume on millennial time scales is a function of temperature and does not depend much on whether the Earth is in a warming or cooling phase. Thus, our simple transparent calculation may provide a useful comparison with geological data for sea-level change and with results of ice sheet models.

We cannot *a priori* define accurately the error in our sea-level estimates, but we can compare with geological data in specific cases as a check on reasonableness. Our results (figure 2) yield two instances in the past million years when sea levels have reached heights well above the current sea level: +9.8 m in the Eemian (approx. 120 kyr BP, also known as Marine Isotope Stage 5e or MIS-5e) and +7.1 m in the Holsteinian (approx. 400 kyr BP, also known as MIS-11). Indeed, these are the two interglacial periods in the Late Pleistocene that traditional geological methods identify as probably having a sea level exceeding that in the Holocene. Geological evidence, mainly coral reefs on tectonically stable coasts, was described in the review of Overpeck *et al.* [51] as favouring an Eemian maximum of +4 to more than 6 m. Rohling *et al.* [52] cite many studies concluding that the mean sea level was 4–6 m above the current sea level during the warmest portion of the Eemian, 123–119 kyr BP; note that several of these studies suggest Eemian sea-level fluctuations up to +10 m, and provide the first continuous sea-level data supporting rapid Eemian sea-level fluctuations. Kopp *et al.* [53] made a statistical analysis of data from a large number of sites, concluding that there was a 95% probability that the Eemian sea level reached at least +6.6 m with a 67% probability that it exceeded 8 m.

The Holsteinian sea level is more difficult to reconstruct from geological data because of its age, and there has been a long-standing controversy concerning a substantial body of geological shoreline evidence for a +20 m Late Holsteinian sea level that Hearty and co-workers have found on numerous sites [54 , 55] (numerous pros and cons are contained in the references provided in our present paragraph). Rohling *et al.* [56] note that their temporally continuous Red Sea record 'strongly supports the MIS-11 sea level review of Bowen [57], which also places MIS-11 sea level within uncertainties at the present-day level'. This issue is important because both ice core data [29] and ocean sediment core data (see below) indicate that the Holsteinian period was only moderately warmer than the Holocene with similar Earth orbital parameters. We suggest that the resolution of this issue is consistent with our estimate of the approximately +7 m Holsteinian global sea level, and is provided by Raymo & Mitrovica [58], who pointed out the need to make a glacial isostatic adjustment (GIA) correction for post-glacial crustal subsidence at the places where Hearty and others deduced local sea-level change. The uncertainties in GIA modelling led Raymo & Mitrovica [58] to conclude that the peak Holsteinian global sea level was in the range of +6 to 13 m relative to the present. Thus, it seems to us, there is a reasonable resolution of the long-standing Holsteinian controversy, with substantial implications for humanity, as discussed in later sections.

We now address differences between our sea-level estimates and those from ice sheet models. We refer to both the one-dimensional ice sheet modelling of de Boer *et al.* [46], which was used to calculate sea level for the entire Cenozoic era, and the three-dimensional ice sheet model of Bintanja *et al.* [59], which was used for simulations of the past million years. The differences most relevant to humanity occur in the interglacial periods slightly warmer than the Holocene, including the Eemian and Hosteinian, as well as the Pliocene, which may have been as warm as projected for later this century. Both the three-dimensional model of Bintanja *et al.* [59] and the one-dimensional model of de Boer *et al.* [46] yield maximum Eemian and Hosteinian sea levels of approximately 1 m relative to the Holocene. de Boer *et al.* [46] obtain approximately +8 m for the Early Pliocene, which compares with our approximately +15 m.

These differences reveal that the modelled ice sheets are less susceptible to change in response to global temperature variation than our $\delta^{18}O$ analysis. Yet the ice sheet models do a good job of reproducing the sea-level change for climates colder than the Holocene, as shown in figure 2 and electronic supplementary material, figure S2. One possibility is that the ice sheet models are too lethargic for climates warmer than the Holocene. Hansen & Sato [60] point out the sudden change in the responsiveness of the ice sheet model of Bintanja *et al.* [59] when the sea level reaches today's level (figs 3 and 4 of Hansen & Sato [60]) and they note that the empirical sea-level data provide no evidence of such a sudden change. The explanation conceivably lies in the fact that the models have many parameters and their operation includes use of 'targets' [46] that affect the model results, because these choices might yield different results for warmer climates than the results for colder climates. Because of the potential that model development choices might be influenced by expectations of a 'correct' result, it is useful to have estimates independent of the models based on alternative assumptions.

Note that our approach also involves 'targets' based on expected behaviour, albeit simple transparent ones. Our two-legged linear approximation of the sea level (equations (3.3) and (3.4)) assumes that the sea level in the LGM was 120 m lower than today and that the sea level was 60 m higher than today 35 Myr BP. This latter assumption may need to be adjusted if glaciers and ice caps in the Eocene had a volume of tens of metres of sea level. However, Miller *et al.* [61] conclude that there was a sea level fall of approximately 55 m at the Eocene–Oligocene transition, consistent with our assumption that Eocene ice probably did not contain more than approximately 10 m of sea level.

Real-world data for the Earth's sea-level history ultimately must provide assessment of sea-level sensitivity to climate change. A recent comprehensive review [7] reveals that there are still wide uncertainties about the Earth's sea-level history that are especially large for time scales of tens of millions of years or longer, which is long enough for substantial changes in the shape and volume of ocean basins. Gasson *et al.* [7] plot regional (New Jersey) sea level (their fig. 14) against the deep ocean temperature inferred from the magnesium/calcium ratio (Mg/Ca) of deep ocean foraminifera [62], finding evidence for a nonlinear sea-level response to temperature roughly consistent with the modelling of de Boer *et al.* [46]. Sea-level change is limited for Mg/Ca temperatures up to about 5°C above current values, whereupon a rather abrupt sea-level rise of several tens of metres occurs, presumably representing the loss of Antarctic ice. However, the uncertainty in the reconstructed sea level is tens of metres and the uncertainty in the Mg/Ca temperature is sufficient to encompass the result from our $\delta^{18}O$ prescription, which has comparable contributions of ice volume change and deep ocean temperature change at the Late Eocene glaciation of Antarctica.

Furthermore, the potential sea-level rise of most practical importance is the first 15 m above the Holocene level. It is such 'moderate' sea-level change for which we particularly question the projections implied by current ice sheet models. Empirical assessment depends upon real-world sea-level data in periods warmer than the Holocene. There is strong evidence, discussed above, that the sea level was several metres higher in recent warm interglacial periods, consistent with our data interpretation. The Pliocene provides data extension to still warmer climates. Our interpretation of $\delta^{18}O$ data suggests that Early Pliocene sea-level change (due to ice volume change) reached about +15 m, and it also indicates sea-level fluctuations as large as 20–40 m. Sea-level data for Mid-Pliocene warm periods, of comparable warmth to average Early Pliocene conditions (figure 3), suggest sea heights as great as +15–25 m [63 , 64]. Miller *et al.* [61] find a Pliocene sea-level maximum of 22±10 m (95% confidence). GIA creates uncertainty in sea-level reconstructions based on shoreline geological data [65], which could be reduced via appropriately distributed field studies. Dwyer & Chandler [64] separate Pliocene ice volume and temperature in deep ocean $\delta^{18}O$ via ostracode Mg/Ca temperatures, finding sea-level maxima and oscillations comparable to our results. Altogether, the empirical data provide strong evidence against the lethargy and strong hysteresis effects of at least some ice sheet models.

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4. Surface air temperature change

The temperature of most interest to humanity is the surface air temperature. A record of past global surface temperature is required for empirical inference of global climate sensitivity. Given that climate sensitivity can depend on the initial climate state and on the magnitude and sign of the climate forcing, a continuous record of global temperature over a wide range of climate states would be especially useful. Because of the singularly rich climate story in Cenozoic deep ocean $\delta^{18}O$ (figure 1), unrivalled in detail and self-consistency by alternative climate proxies, we use deep ocean $\delta^{18}O$ to provide the fine structure of Cenozoic temperature change. We use surface temperature proxies from the LGM, the Pliocene and the Eocene to calibrate and check the relation between deep ocean and surface temperature change.

The temperature signal in deep ocean $\delta^{18}O$ refers to the sea surface where cold dense water formed and sank to the ocean bottom, the principal location of deep water formation being the Southern Ocean. Empirical data and climate models concur that surface temperature change is generally amplified at high latitudes, which tends to make temperature change at the site of deep water formation an overestimate of global temperature change. Empirical data and climate models also concur that surface temperature change is amplified over land areas, which tends to make temperature change at the site of deep water an underestimate of the global temperature. Hansen *et al.* [5] and Hansen & Sato [60] noted that these two factors were substantially offsetting, and thus they made the assumption that benthic foraminifera provide a good approximation of global mean temperature change for most of the Cenozoic era.

However, this approximation breaks down in the Late Cenozoic for two reasons. First, the deep ocean and high-latitude surface ocean where deep water forms are approaching the freezing point in the Late Cenozoic. As the Earth's surface cools further, cold conditions spread to lower latitudes but polar surface water and the deep ocean cannot become much colder, and thus the benthic foraminifera record a temperature change smaller than the global average surface temperature change [43]. Second, the last 5.33 Myr of the Cenozoic, the Pliocene and Pleistocene, was the time that global cooling reached a degree such that large ice sheets could form in the Northern Hemisphere. When a climate forcing, or a slow climate feedback such as ice sheet formation, occurs in one hemisphere, the temperature change is much larger in the hemisphere with the forcing (cf. examples in Hansen *et al.* [66]). Thus, cooling during the last 5.33 Myr in the Southern Ocean site of deep water formation was smaller than the global average cooling.

We especially want our global surface temperature reconstruction to be accurate for the Pliocene and Pleistocene because the global temperature changes that are expected by the end of this century, if humanity continues to rapidly change atmospheric composition, are of a magnitude comparable to climate change in those epochs [1 , 48]. Fortunately, sufficient information is available on surface temperature change in the Pliocene and Pleistocene to allow us to scale the deep ocean temperature change by appropriate factors, thus retaining the temporal variations in the $\delta^{18}O$ while also having a realistic magnitude for the total temperature change over these epochs.

Pliocene temperature is known quite well because of a long-term effort to reconstruct the climate conditions during the Mid-Pliocene warm period (3.29–2.97 Myr BP) and a coordinated effort to numerically simulate the climate by many modelling groups ([67] and papers referenced therein). The reconstructed Pliocene climate used data for the warmest conditions found in the Mid-Pliocene period, which would be similar to average conditions in the Early Pliocene (figure 3). These boundary conditions were used by eight modelling groups to simulate Pliocene climate with atmospheric general circulation models. Although atmosphere–ocean models have difficulty replicating Pliocene climate, atmospheric models forced by specified surface boundary conditions are expected to be capable of calculating global surface temperature with reasonable accuracy. The eight global models yield Pliocene global warming of 3±1°C relative to the Holocene [68]. This Pliocene warming is an amplification by a factor of 2.5 of the deep ocean temperature change.

Similarly, for the reasons given above, the deep ocean temperature change of 2.25°C between the Holocene and the LGM is surely an underestimate of the surface air temperature change. Unfortunately, there is a wide range of estimates for LGM cooling, approximately 3–6°C, as discussed in §6. Thus, we take 4.5°C as our best estimate for LGM cooling, implying an amplification of surface temperature change by a factor of two relative to deep ocean temperature change for this climate interval.

We obtain an absolute temperature scale using the Jones *et al.* [69] estimate of 14°C as the global mean surface temperature for 1961–1990, which corresponds to approximately 13.9°C for the 1951–1980 base period that we normally use [70] and approximately 14.4°C for the first decade of the twenty-first century. We attach the instrumental temperature record to the palaeo data by assuming that the first decade of the twenty-first century exceeds the Holocene mean by 0.25±0.25°C. Global temperature probably declined over the past several millennia [71], but we suggest that warming of the past century has brought global temperature to a level that now slightly exceeds the Holocene mean, judging from sea-level trends and ice sheet mass loss. Sea level is now rising 3.1 mm per year or 3.1 m per millennium [72], an order of magnitude faster than the rate during the past several thousand years, and Greenland and Antarctica are losing mass at accelerating rates [73 , 74]. Our assumption that global temperature passed the Holocene mean a few decades ago is consistent with the rapid change of ice sheet mass balance in the past few decades [75]. The above concatenation of instrumental and palaeo records yields a Holocene mean of 14.15°C and Holocene maximum (from five-point smoothed $\delta^{18}O$) of 14.3°C at 8.6 kyr BP.

Given a Holocene temperature of 14.15°C and LGM cooling of 4.5°C, the Early Pliocene mean temperature 3°C warmer than the Holocene leads to the following prescription:

$$T_s\ (^\circ C) = 2 \times T_{do} + 12.25^\circ C \quad \text{(Pleistocene)} \qquad 4.1$$

and

$$T_s\ (^\circ C) = 2.5 \times T_{do} + 12.15^\circ C \quad \text{(Pliocene)}. \qquad 4.2$$

This prescription yields a maximum Eemian temperature of 15.56°C, which is approximately 1.4°C warmer than the Holocene mean and approximately 1.8°C warmer than the 1880–1920 mean. Clark & Huybers [76] fit a polynomial to proxy temperatures for the Eemian, finding warming as much as +5°C at high northern latitudes but global warming of +1.7°C 'relative to the present interglacial before industrialization'. Other analyses of Eemian data find global sea surface temperature warmer than the Late Holocene by 0.7±0.6°C [77] and all-surface warming of 2°C [78], all in reasonable accord with our prescription.

Our first estimate of global temperature for the remainder of the Cenozoic assumes that $\Delta T_s = \Delta T_{do}$ prior to 5.33 Myr BP, *i.e.* prior to the Plio-Pleistocene, which yields a peak T_s of approximately 28°C at 50 Myr BP (figure 4). This is at the low end of the range of current multi-proxy measures of sea surface temperature for the Early Eocene Climatic Optimum (EECO) [79 – 81]. Climate models are marginally able to reproduce this level of Eocene warmth, but the models require extraordinarily high CO_2 levels, for example 2240–4480 ppm [82] and 2500–6500 ppm [83], and the quasi-agreement between data and models requires an assumption that some of the proxy temperatures are biased towards summer values. Moreover, taking the proxy sea surface temperature data for the peak Eocene period (55–48 Myr BP) at face value yields a global temperature of 33–34°C (fig. 3 of Bijl *et al.* [84]), which would require an even larger CO_2 amount with the same climate models. Thus, below we also consider the implications for climate sensitivity of an assumption that $\Delta T_s = 1.5 \times \Delta T_{do}$ prior to 5.33 Myr BP, which yields T_s approximately 33°C at 50 Myr BP (see electronic supplementary material, figure S3).

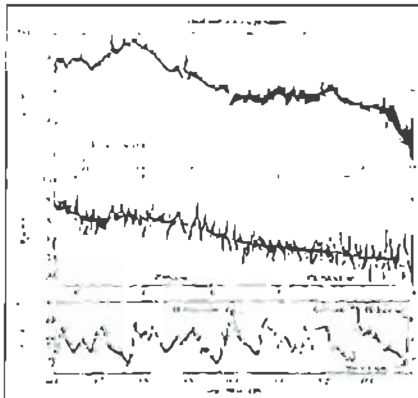

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Figure 4.

(a–c) Surface temperature estimate for the past 65.5 Myr, including an expanded time scale for (b) the Pliocene and Pleistocene and (c) the past 800 000 years. The red curve has a 500 kyr resolution. Data for this and other figures are available in the electronic supplementary material.

5. Climate sensitivity

Climate sensitivity (S) is the equilibrium global surface temperature change (ΔT_{eq}) in response to a specified unit forcing after the planet has come back to energy balance,

$$S = \frac{\Delta T_{eq}}{F}, \quad (5.1)$$

i.e. climate sensitivity is the eventual (equilibrium) global temperature change per unit forcing. Climate sensitivity depends upon climate feedbacks, the many physical processes that come into play as climate changes in response to a forcing. Positive (amplifying) feedbacks increase the climate response, whereas negative (diminishing) feedbacks reduce the response.

We usually discuss climate sensitivity in terms of a global mean temperature response to a $4\,W\,m^{-2}$ CO_2 forcing. One merit of this standard forcing is that its magnitude is similar to an anticipated near-term human-made climate forcing, thus avoiding the need to continually scale the unit sensitivity to achieve an applicable magnitude. A second merit is that the efficacy of forcings varies from one forcing mechanism to another [66]; so it is useful to use the forcing mechanism of greatest interest. Finally, the $4\,W\,m^{-2}$ CO_2 forcing avoids the uncertainty in the exact magnitude of a doubled CO_2 forcing [1 , 48] estimate of $3.7\,W\,m^{-2}$ for doubled CO_2, whereas Hansen *et al.* [66] obtain $4.1\,W\,m^{-2}$, as well as problems associated with the fact that a doubled CO_2 forcing varies as the CO_2 amount changes (the assumption that each CO_2 doubling has the same forcing is meant to approximate the effect of CO_2 absorption line saturation, but actually the forcing per doubling increases as CO_2 increases [66 , 85]).

Climate feedbacks are the core of the climate problem. Climate feedbacks can be confusing, because in climate analyses what is sometimes a climate forcing is at other times a climate feedback. A CO_2 decrease from, say, approximately 1000 ppm in the Early Cenozoic to 170–300 ppm in the Pleistocene, caused by shifting plate tectonics, is a climate forcing, a perturbation of the Earth's energy balance that alters the temperature. Glacial–interglacial oscillations of the CO_2 amount and ice sheet size are both slow climate feedbacks, because glacial–interglacial climate oscillations largely are instigated by insolation changes as the Earth's orbit and tilt of its spin axis change, with the climate change then amplified by a nearly coincident change of the CO_2 amount and the surface albedo. However, for the sake of analysis, we can also choose and compare periods that are in quasi-equilibrium, periods during which there was little change of the ice sheet size or the GHG amount. For example, we can compare conditions averaged over several millennia in the LGM with mean Holocene conditions. The Earth's average energy imbalance within each of these periods had to be a small fraction of $1\,W\,m^{-2}$. Such a planetary energy imbalance is very small compared with the boundary condition 'forcings', such as changed GHG amount and changed surface albedo that maintain the glacial-to-interglacial climate change.

(a) Fast-feedback sensitivity: Last Glacial Maximum–Holocene

The average fast-feedback climate sensitivity over the LGM–Holocene range of climate states can be assessed by comparing estimated global temperature change and climate forcing change between those two climate states [3 , 86]. The appropriate climate forcings are the changes in long-lived GHGs and surface properties on the planet. Fast feedbacks include water vapour, clouds, aerosols and sea ice changes.

This fast-feedback sensitivity is relevant to estimating the climate impact of human-made climate forcings, because the size of ice sheets is not expected to change significantly in decades or even in a century and GHGs can be specified as a forcing. GHGs change in response to climate change, but it is common to include these feedbacks as part of the climate forcing by using observed GHG changes for the past and calculated GHGs for the future, with calculated amounts based on carbon cycle and atmospheric chemistry models.

Climate forcings due to past changes in GHGs and surface albedo can be computed for the past 800 000 years using data from polar ice cores and ocean sediment cores. We use CO_2 [87] and CH_4 [88] data from Antarctic ice cores (figure 5a) to calculate an effective GHG forcing as follows:

$$\mathrm{Fe(GHGs)} = 1.12[\mathrm{Fa(CO_2)} + 1.4\mathrm{Fa(CH_4)}], \quad (5.2)$$

where Fa is the adjusted forcing, i.e. the planetary energy imbalance due to the GHG change after the stratospheric temperature has time to adjust to the gas change. Fe, the effective forcing, accounts for variable efficacies of different climate forcings [66]. Formulae for Fa of each gas are given by Hansen *et al.* [89]. The factor 1.4 converts the adjusted forcing of CH_4 to its effective forcing, Fe, which is greater than Fa mainly because of the effect of CH_4 on the tropospheric ozone and the stratospheric water vapour [66]. The factor 1.12 approximates the forcing by N_2O changes, which are not as well preserved in the ice cores but have a strong positive correlation with CO_2 and CH_4 changes [90]. The factor 1.12 is smaller than the 1.15 used by Hansen *et al.* [91], and is consistent with estimates of the N_2O forcing in the current Goddard Institute for Space Studies (GISS) radiation code and that of the Intergovernmental Panel on Climate Change (IPCC) [1 , 48]. Our LGM–Holocene GHG forcing (figure 5c) is approximately $3\,m^{-2}$, moderately larger than the $2.8\,W\,m^{-2}$ estimated by IPCC [1 , 48] because of our larger effective CH_4 forcing.

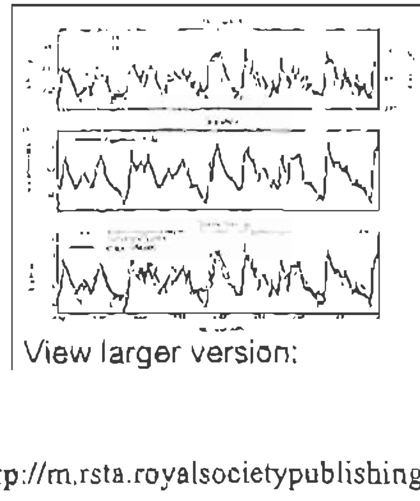

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Figure 5.

(*a*) CO_2 and CH_4 from ice cores; (*b*) sea level from equation (3.4) and (*c*) resulting climate forcings (see text).

Climate forcing due to surface albedo change is a function mainly of the sea level, which implicitly defines ice sheet size. Albedo change due to LGM–Holocene vegetation change, much of which is inherent with ice sheet area change, and albedo change due to coastline movement are lumped together with ice sheet area change in calculating the surface albedo climate forcing. An ice sheet forcing does not depend sensitively on the ice sheet shape or on how many ice sheets the ice volume is divided among and is nearly linear in sea-level change (see electronic supplementary material, figure S4, and [5]). For the sake of simplicity, we use the linear relation in Hansen *et al.* [5] and electronic supplementary material, figure S4; thus, 5 $W m^{-2}$ between the LGM and ice-free conditions and 3.4 $W m^{-2}$ between the LGM and Holocene. This scale factor was based on simulations with an early climate model [3 , 92]; comparable forcings are found in other models (e.g. see discussion in [93]), but results depend on cloud representations, assumed ice albedo and other factors; so the uncertainty is difficult to quantify. We subjectively estimate an uncertainty of approximately 20%.

Global temperature change obtained by multiplying the sum of the two climate forcings in figure 5*c* by a sensitivity of 3/4°C per $W m^{-2}$ yields a remarkably good fit to 'observations' (figure 6), where the observed temperature is $2\times\Delta T_{do}$, with 2 being the scale factor required to yield the estimated 4.5°C LGM–Holocene surface temperature change. The close match is partly a result of the fact that sea-level and temperature data are derived from the same deep ocean record, but use of other sea-level reconstructions still yields a good fit between the calculated and observed temperature [5]. However, exactly the same match as in figure 6 is achieved with a fast-feedback sensitivity of 1°C per $W m^{-2}$ if the LGM cooling is 6°C or with a sensitivity of 0.5°C per $W m^{-2}$ if the LGM cooling is 3°C.

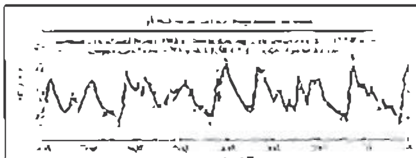

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Figure 6.

Calculated surface temperature for forcings of figure 5*c* with a climate sensitivity of 0.75°C per $W m^{-2}$, compared with $2\times\Delta T_{do}$. Zero point is the Holocene (10 kyr) mean.

Accurate data defining LGM–Holocene warming would aid empirical evaluation of fast-feedback climate sensitivity. Remarkably, the range of recent estimates of LGM–Holocene warming, from approximately 3°C [94] to approximately 6°C [95], is about the same as at the time of the CLIMAP [96] project. Given today's much improved analytic capabilities, a new project to define LGM climate conditions, analogous to the Pliocene Research, Interpretation and Synoptic Mapping (PRISM) Pliocene data reconstruction [97 , 98] and Pliocene Model Intercomparison Project (PlioMIP) model intercomparisons [67 , 68], could be beneficial. In §7*b*, we suggest that a study of Eemian glacial–interglacial climate change could be even more definitive. Combined LGM, Eemian and Pliocene studies would address an issue raised at a recent workshop [99]: the need to evaluate how climate sensitivity varies as a function of the initial climate state. The calculations below were initiated after the workshop as another way to address that question.

(b) Fast-feedback sensitivity: state dependence

Climate sensitivity must be a strong function of the climate state. Simple climate models show that, when the Earth becomes cold enough for the ice cover to approach the tropics, the amplifying albedo feedback causes rapid ice growth to the Equator: 'snowball Earth' conditions [100]. Real-world complexity, including ocean dynamics, can mute this sharp bifurcation to a temporarily stable state [101], but snowball events have occurred several times in the Earth's history when the younger Sun was dimmer than today [102]. The Earth escaped snowball conditions owing to limited weathering in that state, which allowed volcanic CO_2 to accumulate in the atmosphere until there was enough CO_2 for the high sensitivity to cause rapid deglaciation [103].

Climate sensitivity at the other extreme, as the Earth becomes hotter, is also driven mainly by an H_2O feedback. As climate forcing and temperature increase, the amount of water vapour in the air increases and clouds may change. Increased water vapour makes the atmosphere more opaque in the infrared region that radiates the Earth's heat to space, causing the radiation to emerge from higher colder layers, thus reducing the energy emitted to space. This amplifying feedback has been known for centuries and was described remarkably well by Tyndall [104]. Ingersoll [105] discussed the role of water vapours in the 'runaway greenhouse effect' that caused the surface of Venus to eventually become so hot that carbon was 'baked' from the planet's crust, creating a hothouse climate with almost 100 bars of CO_2 in the air and a surface temperature of about 450°C, a stable state from which there is no escape. Arrival at this terminal state required passing through a 'moist greenhouse' state in which surface water evaporates, water vapour becomes a major constituent of the atmosphere and H_2O is dissociated in the upper atmosphere with the hydrogen slowly escaping to space [106]. That Venus had a primordial ocean, with most of the water subsequently lost to space, is confirmed by the present enrichment of deuterium over ordinary hydrogen by a factor of 100 [107], the heavier deuterium being less efficient in escaping gravity to space.

The physics that must be included to investigate the moist greenhouse is principally: (i) accurate radiation incorporating the spectral variation of gaseous absorption in both the solar radiation and thermal emission spectral regions, (ii) atmospheric dynamics and convection with no specifications favouring artificial atmospheric boundaries, such as between a troposphere and stratosphere, (iii) realistic water vapour physics, including its effect on atmospheric mass and surface pressure, and (iv) cloud properties that respond realistically to climate change. Conventional global climate models are inappropriate, as they contain too much other detail in the form of parametrizations or approximations that break down as climate conditions become extreme.

We use the simplified atmosphere–ocean model of Russell *et al.* [108], which solves the same fundamental equations (conservation of energy, momentum, mass and water substance, and the ideal gas law) as in more elaborate global models. Principal changes in the physics in the current version of the model are use of a step-mountain C-grid atmospheric vertical coordinate [109], addition of a drag in the grid-scale momentum equation in both atmosphere and ocean based on subgrid topography variations, and inclusion of realistic ocean tides based on exact positioning of the Moon and Sun. Radiation is the *k*-distribution method of Lacis & Oinas [110] with 25 *k*-values; the sensitivity of this specific radiation code is documented in detail by Hansen *et al.* [111]. Atmosphere and ocean dynamics are calculated on $3^{\circ}\times4^{\circ}$ Arakawa C-grids. There are 24 atmospheric layers. In our present simulations, the ocean's depth is reduced to 100 m with five layers so as to achieve a rapid equilibrium response to forcings; this depth limitation reduces poleward ocean transport by more than half. Moist convection is based on a test of moist static stability as in Hansen *et al.* [92]. Two cloud types occur: moist convective clouds, when the atmosphere is moist statically unstable, and large-scale super-saturation, with cloud optical properties based on the amount of moisture removed to eliminate super-saturation, with scaling coefficients chosen to optimize the control run's fit with global observations [108 , 112]. To avoid long response times in extreme climates, today's ice sheets are assigned surface properties of the tundra, thus allowing them to have a high albedo snow cover in cold climates but darker vegetation in warm climates. The model, the present experiments and more extensive experiments will be described in a forthcoming paper [112].

The equilibrium response of the control run (1950 atmospheric composition, CO_2 approx. 310 ppm) and runs with successive CO_2 doublings and halvings reveals that snowball Earth instability occurs just beyond three CO_2 halvings. Given that a CO_2 doubling or halving is equivalent to a 2% change in solar irradiance [66] and the estimate that solar irradiance was approximately 6% lower 600 Ma at the most recent snowball Earth occurrence [113], figure 7 implies that about 300 ppm CO_2 or less was sufficiently small to initiate glaciation at that time.

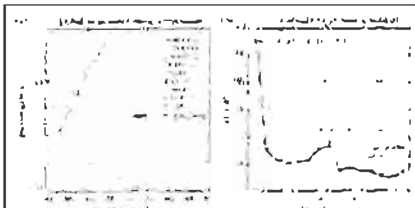

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Figure 7.

(*a*) The calculated global mean temperature for successive doublings of CO_2 (legend identifies every other case) and (*b*) the resulting climate sensitivity ($1\times CO_2$=310 ppm).

Climate sensitivity reaches large values at 8–32×CO_2 (approx. 2500–10 000 ppm; figure 7*b*). High sensitivity is caused by increasing water vapour as the tropopause rises and diminishing low cloud cover, but the sensitivity decreases for still larger CO_2 as cloud optical thickness and planetary albedo increase, as shown by Russell *et al.* [112]. The high sensitivity for CO_2 less than 4×CO_2 is due partly to the nature of the experiments (Greenland and Antarctic ice sheets being replaced by the tundra). High albedo snow cover on these continents largely disappears between 1×CO_2 and 4×CO_2, thus elevating the calculated fast-feedback sensitivity from approximately 4°C to approximately 5°C. In the real world, we would expect the Greenland and Antarctic ice sheets to be nearly eliminated and replaced by partially vegetated surfaces already at 2×CO_2 (620 ppm) equilibrium climate. In other words, if the Greenland/Antarctic surface albedo change were identified as a slow feedback, rather than as a fast-feedback snow effect as it is in figure 7, the fast-feedback sensitivity at 1–4×CO_2 would be approximately 4°C. Thus, the sensitivity approximately 8°C per CO_2 doubling in the range of 8–32×CO_2 is a very large increase over sensitivity at smaller CO_2 amounts.

How confident are we in the modelled fast-feedback sensitivity (figure 7*b*)? We suspect that the modelled water vapour feedback may be moderately exaggerated, because the water vapour amount in the control run exceeds observed amounts. In addition, the area of sea ice in the control run exceeds observations, which may increase the modelled sensitivity in the 1–4×CO_2 range. On the other hand, we probably underestimate the sensitivity at very high CO_2 amounts, because our model (such as most climate models) does not change the total atmospheric mass as the CO_2 amount varies. Mass change due to conceivable fossil fuel loading (up to say 16×CO_2) is unlikely to have much effect, but sensitivity is probably underestimated at high CO_2 amounts owing to self-broadening of CO_2 absorption lines. The increased atmospheric mass is also likely to alter the cloud feedback, which otherwise is a strongly diminishing feedback at very large CO_2 amounts. Atmospheric mass will be important after the Earth has lost its ocean and carbon is baked into the atmosphere. These issues are being examined by Russell *et al.* [112].

Earth today, with approximately 1.26 times 1950 CO_2, is far removed from the snowball state. Because of the increase in solar irradiance over the past 600 Myr and volcanic emissions, no feasible CO_2 amount could take the Earth back to snowball conditions. Similarly, a Venus-like baked-crust CO_2 hothouse is far distant because it cannot occur until the ocean escapes to space. We calculate an escape time of the order of 10^8–10^9 years even with the increased stratospheric water vapour and temperature at 16×CO_2. Given the transient nature of a fossil fuel CO_2 injection, the continuing forcing required to achieve a terminal Venus-like baked-crust CO_2 hothouse must wait until the Sun's brightness has increased on the billion year time scale. However, the planet could become uninhabitable long before that.

The practical concern for humanity is the high climate sensitivity and the eventual climate response that may be reached if all fossil fuels are burned. Estimates of the carbon content of all fossil fuel reservoirs including unconventional fossil fuels such as tar sands, tar shale and various gas reservoirs that can be tapped with developing technology [114] imply that CO_2 conceivably could reach a level as high as 16 times the 1950 atmospheric amount. In that event, figure 7 suggests a global mean warming approaching 25°C, with much larger warming at high latitudes (see electronic supplementary material, figure S6). The result would be a planet on which humans could work and survive outdoors in the summer only in