<u>**Summary of lectures given by Don Paul**</u>

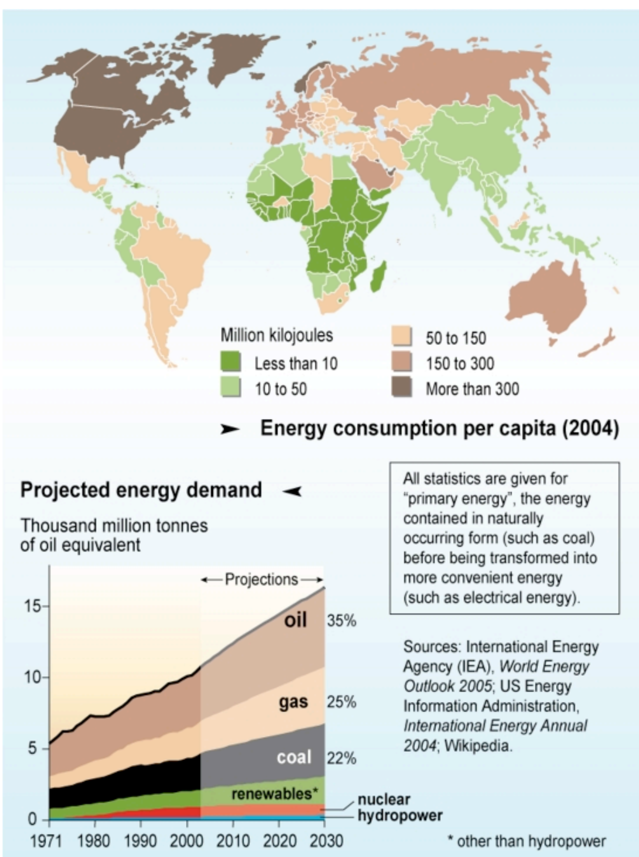
The Global Energy System

Fundamentals

The energy system is about complexity, scale, structure, and time. In this summary, when we refer to the energy system, we mean the global human technical system of harnessing, distributing, and using energy in various forms. There are also important flows of energy through the atmosphere, hydrosphere, biosphere, and lithosphere.

The energy system is about complexity. It consists of elements from three areas of human endeavor: science and technology, economics and business, and politics and society. These three elements interact in a tightly coupled system. Currently, the energy system is led primarily by interests of politics and business. However, in the future, the energy system may be shaped more by forward-looking policies as societies seek to account for current externalities. An example of such policy is a cap and trade system or carbon tax designed to limit greenhouse gas emissions to forestall anthropogenic climate change.

Figure 1: Global per capita energy usage (2004)



The energy system is about scale. In aggregate, huge amounts of resources are devoted to the system. To get an impression of the vast scale of the system, note the following statistics. Global fuel consumption is about one trillion gallons, or roughly one half gallon per person per day. The electricity generation capacity in the United States is about one trillion watts. The world consumed about one trillion barrels of oil over the past 125 years. Both known oil reserves and estimated conventional oil yet to be found total about one trillion barrels. The world contains about one trillion tons of coal reserves. Over the next 25 years, about $20 trillion in capital spending will be needed simply to maintain the current energy system as it exists now.

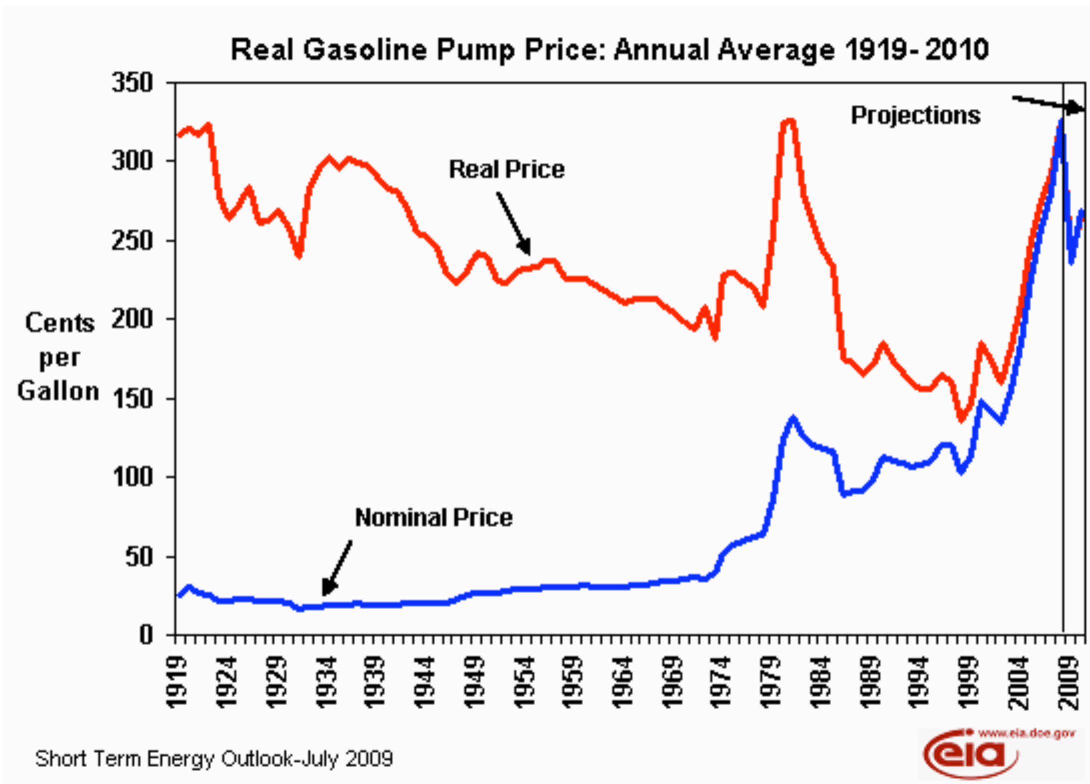
Given the size of the energy system, even changes of one percent in its makeup are vast in scope, cost, and impact. For example, increasing global oil reserves by one percent requires $200 billion in capital investment. Installation of ten gigawatts of photovoltaics in the United States would add one percent to its capacity to generate electric power. The production of corn ethanol in the United States, though it makes up only one percent of liquid fuels globally, is larger than ethanol production in Brazil. As energy technologies scale up, minor effects can grow into large ones (e.g. displacement of food production by corn ethanol) and may have both intended and unintended consequences. Note that the size of the individual technologies in the energy system varies in scale over orders of magnitude, both in linear size and amount of power that flows through them. For example, compare a cell phone charger to a nuclear power plant. The businesses and governments that provide and regulate energy services, respectively, also vary greatly in size.

The energy system is about structure. The energy supply chain consists of three components: electric power, transportation fuel, and natural resource development. All three supply chains contain elements across multiple spatial and temporal scales. Components of the supply chains include land, generation, transport, storage, and distribution. These components are affected by current business models and government regulation. The structure of supply chains also depends on the physical nature of the carrier of the energy, for example electric current as contrasted to liquid hydrocarbons.

The energy system is about time. The history, present, and future of the energy system coexist. Supply and demand for different types of energy varies through time. Multiple generations of energy technology coexist because the lifetime of energy infrastructure is often best measured in decades. Compare this inertia of the energy system to the software industry, where codes can be updated very quickly over a large number of installed computers. The energy system is path dependent. Plans to change the makeup of the energy system require different investments of financial, social, and natural capital depending on the pathway over which they intend to achieve their goals. An understanding of the history of the energy system is needed to understand how to plan for the future. Other types of inertia in the energy system are the dominant business models (including market inefficiencies and externalities), and slowness of many governments to change energy regulations. Note that work (in physics sense) performed to change the state of a thermodynamic system and work (in labor sense) to change the makeup of the energy system are both path dependent.

Some important properties of the energy system can be seen via a look at the history of oil, as seen in the timeline of Table 1. The United States was the dominant actor in the oil market through the middle of the twentieth century. Then the formation of OPEC in 1960, the Santa Barbara blowout and oil spill in 1969, and the Arab oil embargo beginning in 1973 all underscored growing economic, environmental, and strategic vulnerabilities of the country's oil dependence.

Figure 1: Real gasoline pump prices 1919 - 2010 (EIA)



Date	Event	Oil price (US$/bbl)
1870	Standard Oil Trust is formed.	60
1908	Ford Motor Company produces first Model T.	20
1910	US produces 60% of world's oil.	15
1911	Standard Oil Trust is busted.	15
1919	Texas railroad commission regulates Texas oil	25

	production to raise prices and preserve reserves.	
1932	Standard Oil of CA discovers oil in Saudi Arabia.	15
1940-45	US supplies >80% of all oil used in WWII.	15
1956	Interstate Highway System begun (crucial for development of truck transport).	15
1960	OPEC is formed.	15
1968	Prudhoe Bay oil field is discovered.	10
1969	Santa Barbara channel blowout occurs.	10
1970	US oil production peaks.	10
1973	Arab oil embargo begins.	18
1979	Iranian revolution occurs.	45
1989	Exxon Valdez oil spill occurs.	30
1993	China becomes net importer of oil.	20
2009	China becomes largest auto producer.	50

Table 1: A timeline of important events in the history of oil, with prices given in 2007 US$.

Long-Term Trends

The long term trends in the developing energy system are driven, or have the potential to be driven, by global supply and demand growth, development of liquid fuels, efficiency efforts, and decarbonization.

Governments, businesses, and researchers use models to forecast global supply and energy demand. The behavior of such models depends crucially on their underlying assumptions. Only two models, however, treat interacting supply and demand in a dynamic way. Furthermore, most energy system models do not include low-probability high-impact events, colloquially known as black swans. An example of such an event in the oil energy system is the Arab oil embargo of 1973-1974. Most major models use the OECD as a proxy for industrialized countries; the OECD does not include China. Most forecasts have a significant amount of energy efficiency improvements built into the models.

Demand growth is driven by population and energy use per capita, which are both in turn driven by many other factors. The energy demand from OECD countries is expected to be exceeded by non-OECD countries, led by China, by 2010. This crossover reflects a major shift in the energy system. Currently demand growth is being led by the United States, China, and India. The coal sector is expected to undergo the largest growth between now and 2030. The current supply of liquid fuel will decrease. How this supply reduction will be compensated by shifts to electric vehicles, new discoveries of conventional supplies, and unconventional supplies including tar sands, biofuels, and conservation is an open question.

Strategic Issues

The geopolitics of the global energy supply chains is substantial. The countries that consume the largest amounts of energy are in most cases not the largest producers. The coal reserves are the largest fossil source, followed by natural gas and then oil. China is expected to increase its coal consumption greatly over the next 30 years, and is signing long term contracts with suppliers. China currently builds about one coal fired power plant per week, and it aims to achieve 250 coal fired plants in its fleet.

The prospects for decarbonization of the energy supply turn on what happens with coal. If the full cost of carbon was imposed on coal power plants, some exist in locations where they could capture carbon in nearby geologic formations, some could be retrofitted for efficiency, and the rest would close.

Table 2: Largest oil producing and consuming nations.

Largest Producers	**Largest Consumers**
Russia	United States*
Saudi Arabia	China*
United States	Japan*
Iran	Russia
China	India*
Venezuela	Germany*
	* = net importer

Natural gas has much more potential for production than oil, but is harder to transport. The natural gas infrastructure is globalizing, due to increased liquefaction. There are huge unconventional natural gas resources in the United States.

The United States is the world's largest energy producer. It leads the production of nuclear power and renewable energy (power and fuel); it is the second largest producer of coal and natural gas; it possesses the largest unconventional and renewable energy resources. The United States is the world's largest energy consumer, as well, in addition to having the world's largest research and development infrastructure. This confluence of three factors creates opportunities for the United States.

Energy demand in the future will be largely driven by megacities, which are metropolitan areas with more than 20 million people. Megacities are expected to encompass eighty percent of projected population growth. Such cities are not self sufficient and must import food, water, fuel, and so forth. There are twenty four megacities in the world, but only four of them exist in OECD countries. The transportation infrastructure that megacities adopt will have important impacts on fuel demand.

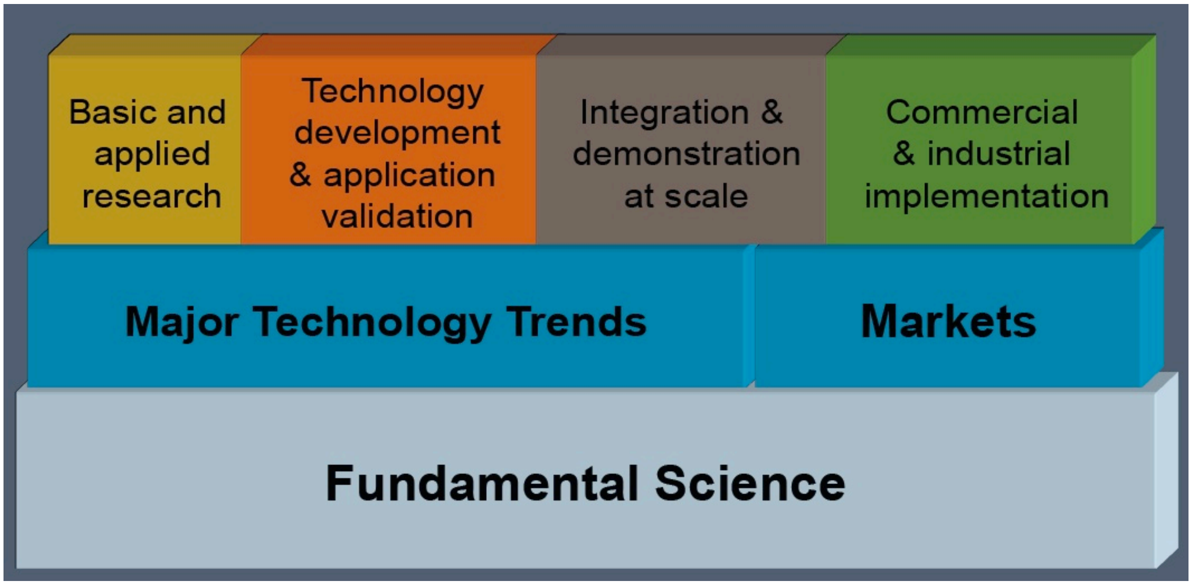
New nuclear power plants are being built in countries other than the United States, which possesses the largest fleet. However, no new nuclear power plants are being built in the United States. As they age and are eventually retired, what will replace them? With fossil and nuclear energy supply technologies, capital cost is expended at the beginning of the project, and then fuel must be purchased on a regular basis. With renewables, the cost of the energy is paid almost entirely at installation (apart from maintenance). Land use is important factor in the development of the energy system. For example permits for power lines can become a big political issue (e.g. due to NIMBY opposition), and mountaintop removal mining of coal has important environmental and social effects. The demand side of the energy system is the most important for effecting change. Efficiency, even though it is partly built into most model forcasts, can still make a large impact. Solar energy could have a huge impact due to its large resource size.

Energy Technology and the Implications for Sustainability

Fundamentals

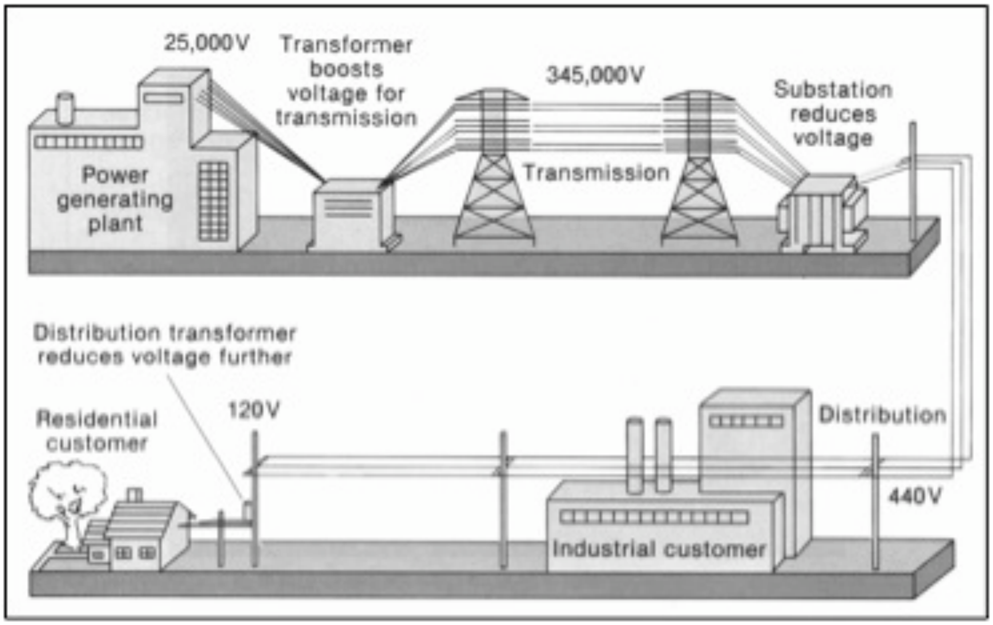
Technology, business, and politics are three drivers of the energy system. The interaction between these three drivers leads to complexity (e.g. path dependence in amount of effort and capital required to change the system). The huge scale of the energy system means that even changes of one percent are large.

Figure 2: Basic components of the energy ecosystem



The component technologies (transformers, engines, power electronics) are linked into application systems and processes (such as manufacturing, policy creation, etc). Both component technologies and these application systems are linked to integrated delivery structures (electric grid, oil and natural gas pipelines, shipping fleet that carries fossil fuels).

Figure 3: Basic example of pathways of production to consumption of electricity



Large scale energy technologies go through a process, which can take on the order of ten years. At each step in the process the capital investment required increases by an order of magnitude. Bench scale prototypes and basic research and development cost on the order of millions US$, pilot plants cost on the order of tens of millions US$, demonstration scale projects cost on the order of hundreds of millions US$, and full scale production (needed to reach even one percent scale) costs billions US$. Many technologies become stalled in their development between the pilot plant and demonstration scale stage.

There are diverse participants in the the system of energy technology development, including governments, universities, non profits, established industry, venture capitalists, and startup companies. To transfer technology from research labs up through the process of implementation, the interests of the various actors must be aligned at each step. Each actor has different motivations, business models, and time frames over which they act. The culture of the participants is a crucial factor that affects the "impedance mismatch" at each step in the development and implementation process. This mismatch is reflected in the following aphorism: academia converts money into knowledge, and industry converts knowledge to money.

Opportunities

Three transcendent technologies will intersect with the energy system in the future. These are information technology, molecular technology, and advanced materials technology. The military (and the defense industry surrounding it) is the primary funder of technology trends. The U.S. military is currently the largest buyer of renewable energy in the U.S.

The advancement of information technology has been driven by the increasing computing power described by Moore's law. This increase has led to an explosion of data, and connections between people that have changed social behavior already. The integration of information technology into the energy system, enabled by these advances, has been driven by need to both increase the efficiency of energy supply chains and manage their complexity. The merger of the information technology system and the energy system in a smart grid would be the combination of the two largest infrastructure systems in use today.

The processing power of this information technology could allow sensors to be placed throughout the built and natural environments to monitor energy use. The processing power also enables mobile robots to be used in much larger numbers than before. They are already seen in warehouses and deployed on military operations, hospitals, and homes (e.g. robot vacuums and floor cleaners). The power used by mobile robots could, as their stationary brethren before them, become a relatively small but significant source of energy demand (as the data centers that make up the internet have become).

The increasing complexity of the energy system will require a sophisticated layer of computer control between the actual machinery of the system and the human operators, because the volume of data collected by the system and the speed with which it is collected will overwhelm any human. Therefore the system will have to be partially controlled by machine, and only certain metrics will be ordinarily displayed to the operators. The complexity of the energy system, particular the electric power system, will be driven by the likely adoption of a smart grid that can partially control demand, as well as increased use of more variable power producing installations such as wind and solar farms.

The use of information technology in the smart grid will increase the possibility of electronic attacks against the grid. The increased number of elements in the smart grid may lead to instabilities; this development has led to a revival of nonlinear systems theory to attempt to forestall such failures. The integration of more information technology into the electric power grid, once completed, will not be undone. Historically once digital technology is integrated into a technical system, it is not removed.

Advances in molecular transformation technology (i.e. chemistry, broadly defined) will allow allow humans to more easily transform diverse feedstocks into desired products. These processes include both traditional thermo-chemical processing along with biology, including synthetic biology. Synthetic biology refers to the creation of standardized biological components (strains of bacteria and gene sequences) that can be combined together in controlled ways to produce specific products, such as fuel. Thermo-chemical and biological processing of fuels and lubricants will likely converge some time in the future.

Feedstock diversification is being driven by demand due to changes in the number of automobiles (e.g. driven in part by changes in social norms) and more strict fuel standards, and is enabled by advances in information technology, chemistry, and advanced materials. Green supply chains and super efficiency are being driven by standards, capital efficiency, lower operating costs, and expanded markets. They are enabled by universal spread of information technology, advanced materials, and manufacturing. The decarbonization of coal is driven by the large installed base of coal fired power plants and the large coal resource, carbon regulations, and possibility for synthetic fuels. The enablers of this technology are advances in separation and purification technology, and conversion and molecular transformation technologies.

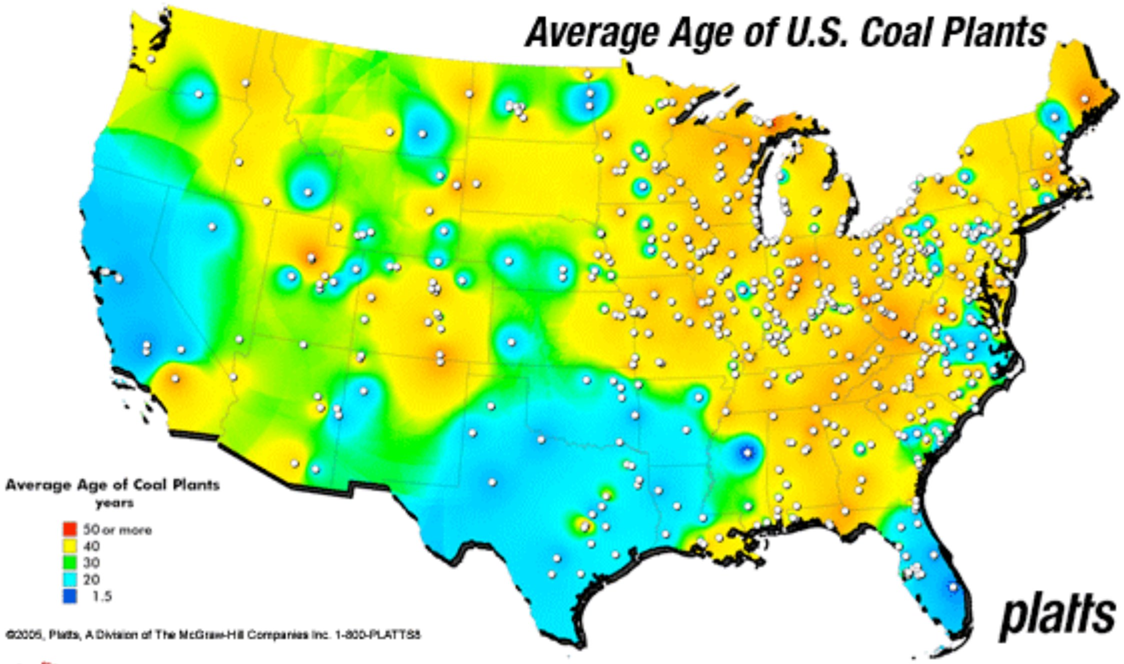
Opportunities pushed the adoption of energy technology, not the other way around. Just because a new technology is developed does not mean that it will be deployed into the energy system. The technology must do one or more of the following: improve economic performance, extend existing resources or substitute (in a simple way) for an existing resource, diversify demand options, or manage carbon at scale. Energy research is funded approximately three-fourths by industry and one fourth by public means. The government has a key role in developing science and technology trends that contribute to technology for the energy system.

Necessity and performance of technology is not sufficient for it to be adopted. Substitution markets are much more difficult to enter than growth markets. There are evolving finance and business models for efficiency, renewable sources, and resource switching. Standards are more important on the demand side. Energy is typically a commodity, but it might be branded by emphasis on reliability or "green power".

Next Wave

Some of the next wave of energy technology includes electrical storage at scale, the use of carbon dioxide as a feedstock, resource switching, and new devices that will be consumers of electricity. Lock in effects are important in the energy system; we drag our history along with us in the energy system. Water is important: energy manages water, and water manages energy. It is hoped that the sustainability focus will broaden beyond carbon to include water, food, and other issues.

Figure 3a and 3b: Average age of nuclear (a) and coal (b) plants in the United States



YEARS OF COMMERCIAL OPERATION	NUMBER OF REACTORS	AVERAGE CAPACITY (MDC)
△ 0–9	2	1134
▲ 10–19	47	1092
▲ 20–29	55	779

Note: There are no commercial reactors in Alaska or Hawaii. Calculated data as of 12/00.