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Energy Portfolio Assessment Tool (EPAT): Sustainable energy planning using the WEF nexus approach – Texas case

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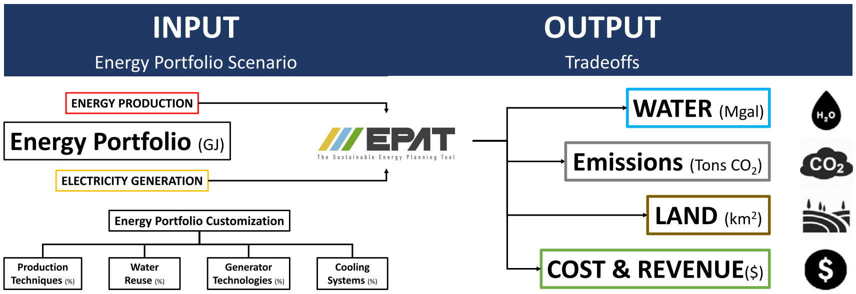
HIGHLIGHTS

- Energy planning must be supported by holistic nexus methodologies in line with sustainable development pillars
- Energy Portfolio Assessment Tool (EPAT) is a nexus platform for energy policy tradeoff analysis
- Some conservation policies have unintended consequences and should be evaluated prior to execution

GRAPHICAL ABSTRACT



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ABSTRACT

The paper introduces a holistic framework that identifies the links between energy and other systems (water, land, environment, finance, etc.), and measures the impact of energy portfolios, to offer a solid foundation for the best sustainable decision making in energy planning. The paper presents a scenario-based holistic nexus tool, Energy Portfolio Assessment Tool (EPAT) that provides a platform for energy stakeholders and policymakers to create and evaluate the sustainability of various scenarios based on the water-energy-food (WEF) nexus approach. The tool is applied to a case study in Texas, USA. Scenarios considered are set by the U.S. Energy Information Administration (EIA): EIA Reference Case – 2015, EIA Clean Power Plan (CPP) & Reference Case - 2030, and EIA No-CPP & Reference Case - 2030. In the presence of the CPP, total water withdrawal is expected to decrease significantly, while total water consumption is projected to experience a slight decrease due to the increase in water consumption in electricity generation caused by the new electricity mix. The CPP is successful in decreasing emissions, but is accompanied by tradeoffs, such as increased water consumption and land use by electricity generation. The absence of the CPP will lead to an extreme surge in total water withdrawn and consumed, and in emissions. Therefore, conservation policies should move from the silo to the nexus mentality to avoid unintended consequences that result in improving one part of the nexus while worsening the other parts.

1. Introduction

From a political perspective, the term ‘energy security’ is commonly perceived by policy makers to mean safeguarding a continuous supply of energy. However, of equal importance to ‘energy security’ is the

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notion of sustainable energy supply, give the interdependence of energy with natural resources such as water, land, and even climate. To date, there is no precise consensus on the two (Kruyt et al., 2009). It is essential, for the modern economy, to produce sufficient energy to meet the growing demand: energy is the fuel of the engine driving the economy. At the same time, unclean energy and or its unsustainable production make the process of energy security a complex challenge (Obaidullah et al., 2016). Mishandling natural resources poses serious threats to a nation's future water, energy, food (WEF), and land securities. Policy makers governing energy, water and other resources are the major stakeholders in the journey to a sustainable future (Daher and Mohtar, 2015). Thus far, the focus of energy policy makers has been solely on securing the supply of energy and electricity demanded by growing populations and economies. In a rapidly changing world, climate change is a serious global concern, clean renewable energy technologies are advancing at unprecedented rates; water-energy efficient technologies are vastly improved; and competition for natural resources such as water and land is increasingly fierce. In a world where natural resources were viewed as abundant, sufficient, accessible, and without threat from climate challenges, failure to consider the tradeoffs between resource allocation strategies appeared less threatening. However, the world is increasingly cognizant of serious global concerns and increasing competition for finite natural resources, including land and water, and especially as the impacts of a changing climate are increasingly felt by all.

A better understanding of the impacts of the systems on one another can assist policy makers by showing the benefits of a holistic assessment framework for the interconnected systems and quantifying the resulting tradeoffs (Mohtar and Daher, 2012). Scenario-based assessment tools enable policy makers to plan and select more sustainable energy portfolios for the future. Appropriate policies that acknowledge and respect the WEF interlinkages are fundamental to mitigating future energy, water, and other resource security risks.

Using energy as a focal point, all phases of energy production and electricity generation consume water. Global energy demand is rising; consequently, the water demanded by the energy sector is also rising. Yet, to date, water and energy are regulated independently of one another (Hussey and Pittock, 2012).

The resource nexus has only recently become a point of interest for research and public policy making (Webber et al., 2008). Experience has taught that while working in silos does create effective water and energy policies, it often results in the policy makers disregarding the interconnectedness of water and energy, producing separate and contradictory policies for the two sectors (Poumadere et al., 2005). Water policy makers seek optimal solutions that ensure the sustainability of water resources. At the same time, energy policy makers seek to ensure energy resources. From a sustainability perspective, neither results in a truly optimal solution because the systems were considered to be uncoupled: working in silos exposes both the water and the energy systems to vulnerabilities such as drought, heat waves, contamination, grid outages, and unfair competition for water resources.

Given the global dwindling of water resources and the challenges of its availability, high reliance on water-intensive technologies to meet energy demands puts the US energy sector at risk: water is neither temporally nor spatially evenly distributed across the United States (DOE, 2014). If one considers water as a “pie”, with the energy, food, municipal, industrial, and other sectors competing to secure shares of the water pie, then securing water presents a challenge to energy policy makers. Although inefficient, unsustainable water allocation strategies may currently work, as populations grow, economies expand, and climate change worsens, the vulnerabilities within the energy system will increasingly appear and expand (Intergovernmental Panel on Climate Change, 2008).

Questions arise, such as: how should the energy production portfolio be altered to reduce its water footprint, yet still meet demand; how can the electricity generation portfolio be changed to be less water intensive but still reliable; what adjustments are required in the energy technology portfolio; what are the environmental, land, and economic costs of such adjustments? The inclusive, sustainable energy planning offered by the WEF platform addresses these questions, but requires a deep understanding of the interconnections between the associated systems (energy, water, land, environment, economics) and the accompanying sustainability tradeoffs comprising in proposed scenarios. This paper presents a unique scenario-based framework and tool together with its application to a Texas case study, namely the Energy Portfolio Assessment Tool (EPAT).

1.1. Research objectives

1. Develop a tool to assess the sustainability of energy portfolios through quantification of the tradeoffs between water, environment, land, and energy economics.
2. Use the developed Energy Portfolio Assessment Tool (EPAT) to assess the sustainability and tradeoffs of current and projected energy portfolios of the US Energy Information Administration (EIA) in Texas, considering sustainable energy development, water conservation, environmental impact, and energy economics.

2. Literature review

2.1. Water-energy-food nexus

It is increasingly clear to the world that water, energy, and food (WEF) are deeply interconnected systems also intensely linked with economic and environmental sustainability (Bhaduri et al., 2015). Water, energy, and food securities are interdependent, as evidenced in simple examples: water extraction, treatment, and transport demand energy; energy production and electricity generation require water; and food production needs both water and energy. The linkages between the WEF systems are intensified with increased natural resource scarcity, environmental pressure, climate change, and population growth (Mohtar and Daher, 2012). Recognizing these interlinkages in natural resource systems implies that a holistic nexus methodology could support decisions toward sustainable development: such an approach builds synergies and quantifies tradeoffs between the WEF systems, to the benefit of both humans and nature, and to increased efficiency in the management of water, energy and food resources. Historically, development and policy work have overlooked the real costs to environment, due in part to opposition to the systematic methodologies that consider these linkages across sectors and resources (Bhaduri et al., 2015).

A key goal of the water-energy-food nexus approach is to reduce carbon-intensive water, energy, and food production. This paper focuses on the energy aspect of the nexus, and renewable energy is the perfect solution because renewable energy supplies are naturally harvested from sources such as the sun, wind, and water. Looking at outputs, in renewable energy power generation process does not require combustion thus is technically a zero carbon source of power, thus apparently sustainable. However, sustainability refers not only to infinite sources, but also to a non-detrimental supply of the renewable resources, economically, environmentally and socially (Owusu and Asumadu-Sarkodie, 2016). For instance, a sustainable biofuel resource should not increase the net greenhouse gas emissions, should not affect food security, and should not affect water security (Twidell and Weir, 2015). However, the water-energy-food nexus methodology for natural resource management ensures efficient, productive, and sustainable utilization of natural resources by looking at the three resources as a single system of systems.

The WEF Nexus approach supports policy and decision makers in achieving several sustainability goals by:

- quantifying interlinkages between water, energy, and food,
- identifying existing and potential hotspots,
- accounting for trade-offs in policy and strategy selections,
- informing important scientific dialogue at the policy level.

The WEF nexus analytics platform is not sector-centric. The dialogue it enables is inclusive and supports all existing initiatives for water resource management, energy efficiency and food production efficiency (Mohtar, 2015).

2.2. Knowledge gap and tool review

Policy makers can benefit from a holistic framework that illustrates the connections between the associated systems and displays the resulting tradeoffs, making it possible to better understand the manner in which the separate systems impact one another (Mohtar and Daher, 2012). The policy maker lacks efficient tools to evaluate the sustainability of energy portfolios and demonstrate the consequent trade-offs across nexus systems. Integrating the methodology of sustainable development measures into national energy policies, strategies and planning by promoting interdisciplinary scientific research and technology development will increase institutional capacity by offering early warnings and impacting energy planning (Asumadu-Sarkodie and Owusu, 2017).

Tools that address both general and specific aspects of energy impact within the nexus already exist and include LEAP (SEI, 2013), CLEWS (KTH, 2013), Global Calculator (Strapasson et al., 2014), among many others. LEAP (Long-range Energy Alternatives Planning System) is a tool that analyses the effects of energy policy on climate and assesses mitigation approaches to climate change. CLEWS (Climate, Land, Energy and Water Strategies) use a systems approach to determine and address issues of interconnected resources and their interactions. Global Calculator is a tool that links energy to lifestyle to illustrate the consequences of pathways in energy, food, and land on the climate. A more complete list of nexus tools can be found in IRENA (2015).

All these tools address the energy part of the nexus; each has a unique approach to analyzing the interactions of energy resources with climate and land. However, even with all the existing tools, the policy maker still lacks a comprehensive, multi-scale energy assessment tool capable of quantifying interconnectivity (between energy, water, land, climate and economics). In short, a generic, holistic framework that considers the existing interlinkages between the systems and offers decision/policy-makers a solid foundation for debate, discussion and action (Table 1).

3. Methodology

3.1. Conceptual scenario framework

The energy portfolio is generally governed by policy choices that are driven by preferences, either toward an expensive, sustainable, secure energy portfolio, or toward an inexpensive, unsustainable, secure energy portfolio. The feasibility of a given energy scenario should respect the interconnections between the systems: the foundation of any portfolio assessment initiative.

Energy production and electricity generation are directly linked to water, land, environment, and financials. Energy production includes extraction, transport, and refining. Each component of energy production has a water, land, and carbon footprint and is associated with a financial measure. Similarly, electricity represented by its various facades of generation, is associated with water and land as inputs and carries financial and environmental costs. State and municipal energy portfolios are increasingly vulnerable due to the direct link with and reliance upon natural resource systems. At the same time, local natural resources are at risk of exploitation. Vulnerabilities are characterized by non-sustainable water planning in energy activities, high competition for land, environmental concerns, and lack of financial affordability. Moderating this high dependence on natural resources and ensuring sustainable energy planning that is compatible with the conservation of natural resources require an understanding of the requirements accompanying energy security and the ability of a state to secure sustainable energy portfolios. Considerations for energy portfolio development and policies should include the tradeoffs described below.

3.1.1. Water

Quantify the water demands for any energy portfolio scenario. Water use in energy production and electricity generation depends on production techniques, water reuse, generation technologies, and cooling systems.

Table 1
Review of nexus tools (IRENA, 2015; Strapasson et al., 2014).

Tools	Inputs		Outputs	
	Main inputs	Energy	Water	Food
LEAP	Extensive data requirement. Techno-economic details of energy technologies.	Detailed analysis of energy demand, transformations and stocks. Energy balances.	Watershed hydrology and water planning. Physical and geographical simulation water demands and supplies. Groundwater, water quality and conservation, reservoirs and hydropower.	
CLEW	Extensive data requirements. Technical and economic parameters of power plants, farming machinery, water supply chain, desalination terminals, irrigation technologies, fertilizer production, etc.	Energy balance, including power generation and refining. Energy for Food. Foreign (virtual) energy.	Water balance. Water supply and desalination. Water pumping. Water for food. Water for energy (hydropower, power plant cooling, biofuel crops).	Irrigation technologies. Use of fertilizers. Use of farming machinery.
Global Calculator	Global scale. Minimum data available. Very general.	Fixed pre-created global energy scenarios. Very general and basic technology and fuel alteration.		Land use. Farm yields and practices. Very basic and general diet alteration.

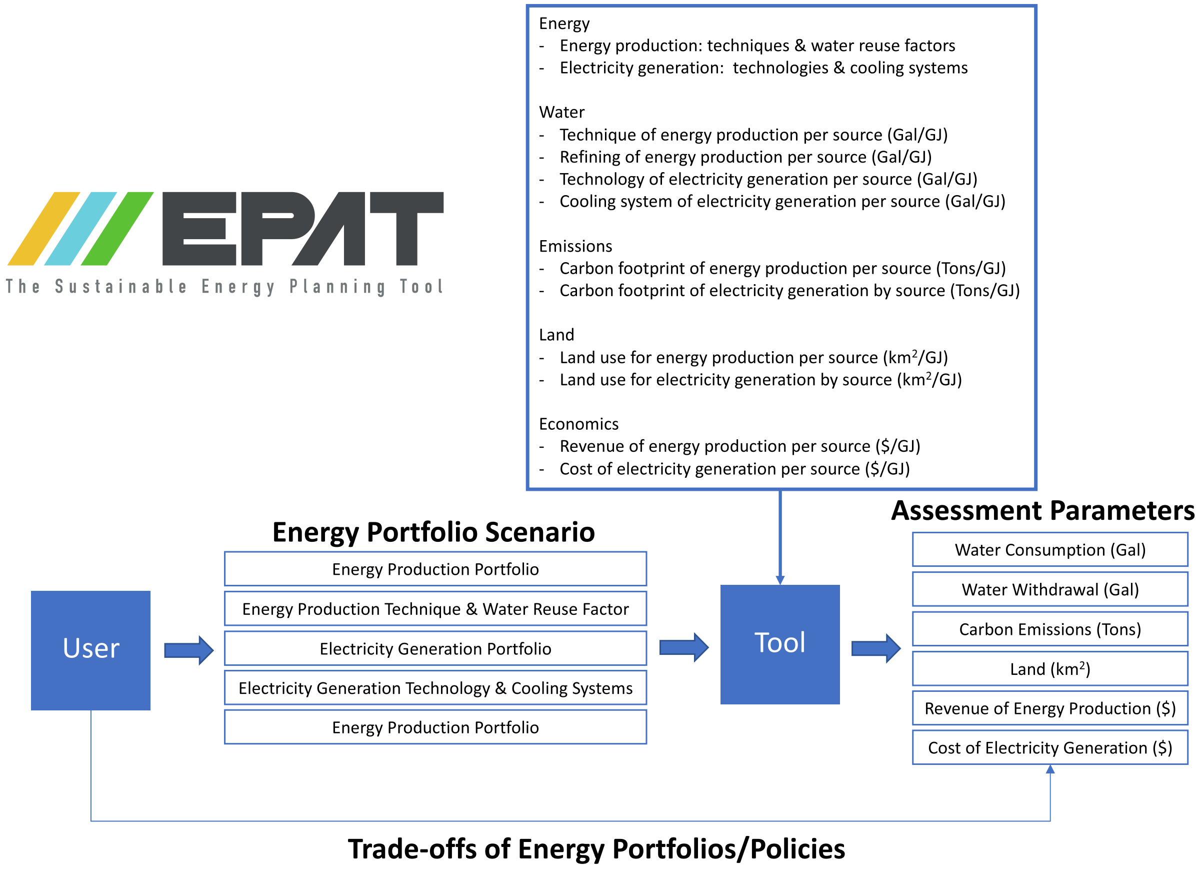

Fig. 1. Tool structure: input-output.

3.1.2. Environment

Quantify the environmental impact of energy portfolio scenarios on the atmosphere. The amount of carbon emitted depends on both the energy produced and the electricity generation mix; it is also associated with the intensity of the energy demanded for the scenario.

3.1.3. Land

Quantify land use for each energy portfolio scenario. Land used in energy production and electricity generation depends not only on the energy and electricity mix, but also on the total energy demand intensity.

3.1.4. Economics

Quantify the revenue from energy production and the cost of electricity generation as the economic measures of the energy portfolio scenario.

3.2. Energy Portfolio Assessment Tool (EPAT) Framework

Having defined the technicality of energy portfolios and their interconnections with other systems, this section introduces the structure of the Energy Portfolio Assessment Tool (EPAT). The Tool was developed using the Water-Energy-Food (WEF) Nexus systemic approach to integrated energy portfolio systems. It offers an alternative to the 'silo' approach and addresses the associated environmental and economic systems. EPAT is a scenario-based tool that enables the policy maker to create an energy portfolio scenario using various energy and electricity sources. It then evaluates the environmental and economic sustainability of the scenario. The tool assesses various energy portfolio options, taking as input energy production and electricity generation mix (in Giga Joules), and generating quantitative parameters in terms of water withdrawal and consumption (Million Gallons), economics of energy and electricity (US Dollars), carbon emissions (Ton CO_2), and land required (km^2).

The tool framework is energy-centric, allowing the user to apply it to any given governance or geographic area. The impact and tradeoffs of each energy portfolio are evaluated using two sets of data as input: energy production and electricity generation (Fig. 1).

An energy portfolio comprises two sub portfolios: energy production and electricity generation. Energy production corresponds to the physical energy volume mix; electricity generation is the mix of electricity generation sources. There is a link between energy production and electricity generation portfolios: the first is the input of the second. EPAT assesses each system separately, using a two-step input framework: first, the definition of the total energy portfolio, and second, its customization.

The user creates the scenario by inserting the following inputs:

- Defining the energy portfolio requires the input of the energy and electricity portfolios by source (GJ/source). The sources of energy production embedded in the tool include: oil, natural gas, coal, and bioenergy. The sources of electricity generation embedded in the tool include: natural gas, coal, nuclear, wind, hydro and solar.

Table 2
Notations and water factors for oil production used in EPAT.

Oil (OL)			
i	$PTOL_i$	$WPOL_i$ (gal/GJ)	WROL (gal/GJ)
1	Primary	1	7
2	EOR	91	

Table 3
Notations and water factors for natural gas production used in EPAT.

Natural gas (NG)			
i	$PTNG_i$	$WPNG_i$ (gal/GJ)	WRNG (gal/GJ)
1	Conventional	0.11	2
2	Unconventional	3	

Table 5
Notations and water factors for bioenergy used in EPAT.

Bioenergy (BE)		
i	$PTBE_i$	$WPBE_i$ (gal/GJ)
1	Ethanol from corn	198
2	Biodiesel from soy	438

- After inputting the portfolio, the user can independently customize the energy production and electricity generation portfolios in terms of production techniques, water reuse, generation technologies, and cooling systems.

The strength of EPAT lies in this customization step: for the same portfolio, each customization has a unique end tradeoff result. For example, in energy production, natural gas came 20% from conventional techniques and 80% from unconventional techniques with 100% refined, and 10% water reuse. An example in electricity generation could be: total coal electricity generated was 100% with steam turbine generator technology, and a cooling portfolio of 70% once-through, 20% cooling tower and 10% recirculating reservoir. Given the scenario energy portfolio inputs, and based on the customization of the sub-portfolios, the tool assesses the proposed scenario by quantifying the following tradeoffs:

- Total water consumed for energy production in the scenario WCEP (million gallons).
- Total water consumed for electricity generation in the scenario WCEG (million gallons).
- Total water withdrawn for electricity generation in the scenario WWEG (million gallons).
- Total land requirement for energy production in the scenario LEP (km^2)
- Total land requirement for electricity generation in the scenario LEG (km^2)
- Total carbon emissions from energy production in the scenario EEP (Tons CO_2)
- Total carbon emissions from electricity generation in the scenario EEG (Tons CO_2)
- Total revenue from energy production in the scenario REP (US $)
- Total cost of electricity generation in the scenario CEG (US $)

While the structure of the EPAT tool is generic, local customization data are area-specific and play a huge role in quantifying the tradeoffs for a given scenario.

3.3. Quantifying tradeoffs

The presented framework offers a platform that defines the connections between energy, water, environment, land, and economics. The resulting tradeoffs quantification and analysis from these connections is necessary for a complete assessment of various energy scenarios and offers a means to proper decision-making.

An energy portfolio comprises two sub portfolios: energy production and electricity generation. By proposing a scenario, energy produced and electricity generated are quantified in Giga Joules (GJ). The energy production portfolio corresponds to the physical energy volume mix. The tradeoffs of an energy production portfolio are a function of: energy source, production technique, refining percentage, and water reuse factors. Land requirement (km^2) is quantified depending on the choice of production technique. The amount of water consumed (Million Gallons) in energy production processes depends on the extraction technique, refining energy product percentage, and overall water reuse factor in all practices. Water tradeoffs are highly affected by the production technique: each technique has a unique water footprint and varies greatly from one technique to another. More importantly, the concentration of water reuse activities impacts total water tradeoff. Total revenue (US $) of the energy production portfolio is a function of total energy produced and the respective commodity price. In addition, the carbon footprint (Tons CO_2) is quantified based on the amount of energy produced and its mix.

Table 4
Notations and water factors for coal production used in EPAT.

Coal (CO)		
PTCO	WPCO (gal/GJ)	WRCO (gal/GJ)
Avg. surf. & undgrnd.	19	11

The electricity generation portfolio corresponds to the mix of power sources. Tradeoffs of electricity generation depend of the electricity source, generator technology, and cooling system. The amount of water needed (Million Gallons), consumed and withdrawn, are directly linked to the choice of generation technology and cooling system for each source. The water requirement is greatly impacted by the combination of generation technology and cooling systems: water withdrawal and consumption footprints are unique for each combination. The cost (US $) of generation for an electricity portfolio is a function of the electricity sources in the portfolio. Nonetheless, carbon (Tons CO_2) emitted into the atmosphere from electricity generation depends on the electricity sources comprising the total electricity portfolio. Land (km^2) is a major tradeoff in electricity generation: the total land occupied by the electricity portfolio is based not only on the electricity generation source, but also its capacity.

3.3.1. Water for energy production

The quantification of water consumption for energy production requires only 2 steps after the input of the energy production portfolio. For each energy resource, the user must identify the fraction of energy produced per production technique (listed in the tool). The extraction of an energy source is done through multiple techniques; each technique has a unique water footprint. In addition to partitioning production per technique, the user must input the percentage of water reuse through the process. The techniques and calculation of water footprints for all energy sources in the tool are discussed below.

3.3.1.1. Oil. The total amount of water consumed in oil production (WEPOL) is a function of type of production ($PTOL_i$) and refining (WROL). The types of oil production included in the tool are primary and enhanced oil recovery (EOR). Each type has a unique water consumption factor ($WPOL_i$). Therefore, after inserting the total oil

Table 6
Fuel type and efficiencies of generator technologies in EPAT.

Fuel type	Generator technology	Efficiency
Coal	ST	35%
	IGCC	39%
Natural gas	ST	35%
	CC	54%
	GT	59%
Nuclear	ST	35%

Table 7
Notations and water factors for natural gas electricity used in EPAT.

Natural gas (NG)					
i	$GTNU_i$	j	$CTNG_{ij}$	$WCNG_{ij}$ (gal/GJ)	$WWNG_{ij}$ (gal/GJ)
1	CC	1	Once-through	28	2306
		2	Tower	58	69
		3	Dry	1	1
		4	Recirc. res.	67	1653
2	ST	1	Once-through	82	9722
		2	Tower	203	333
3	GT	1	No cooling	2	2

production data (EPOL), the user must specify the fractions of production type, so that each production type matches its water consumption factor to achieve a better water consumption estimate. The percentage of water reuse (RUOL) in oil production must be defined. The refining water consumption factor is applied to the total oil production value; it is assumed that all the oil produced goes through the same refining process. WEPOL is the summation of the water footprint values of oil production types and refining (Table 2).

$$WEPOL = EPOL \times \left[\sum_{i=1}^{2}(PTOL_i \times WPOL_i)(1-RUOL) + WROL\right]$$

3.3.1.2. Natural gas. Two types of natural gas production ($PTNG_i$) are considered in EPAT: conventional and unconventional. Each technique has an associated water footprint ($WPNG_i$). The total natural gas production data (EPNG) is split in ratios, then multiplied with its water consumption tag. The percentage of water reuse (RUNG) in natural gas production is input. The water consumed for refining natural gas is obtained by multiplying the total natural gas production value by the water consumption factor for refining (WRNG). The same refining procedure is assumed for natural gas produced. Table 3 displays natural gas production types, water consumption factors for production and refining, respective notations, and the equation used to calculate the total water consumed for natural gas production (WEPNG).

$$WEPNG = EPNG \times \left[\sum_{i=1}^{2}(PTNG_i \times WPNG_i)(1-RUNG) + WRNG\right]$$

3.3.1.3. Coal. A single technique of production was considered for coal production. The technique (PTCO) is a mix of surface and underground mining; its water consumption factor (WPCO) reflects the average of both techniques. The percentage of water reuse (RUCO) in coal production must be specified to reflect any current water conservation. Similarly, a uniform water consumption factor for refining (WRCO) is assumed to the total coal produced. Then, the total water consumed for coal production and refining (WEPCO) is the multiplication of the total coal energy produced by water factors (Table 4).

$$WEPCO = EPCO \times (WPCO + WRCO)$$

Table 8
Notations and water factors for coal electricity used in EPAT.

COAL (CO)					
i	$GTCO_i$	j	$CTCO_{ij}$	$WCCO_{ij}$ (gal/GJ)	$WWCO_{ij}$ (gal/GJ)
1	ST	1	Once-through	42	9722
		2	Tower	146	181
		3	Recirc. res.	139	3375
2	IGCC	1	Tower	89	104

Table 9
Notations and water factors for nuclear electricity used in EPAT.

Nuclear (NU)				
GTNU	i	$CTNU_i$	$WCNU_i$ (gal/GJ)	$WWNU_i$ (gal/GJ)
ST	1	Once-through	111	12,778
	2	Recirc.res.	178	1889
	3	Tower	200	306

3.3.1.4. Bioenergy. Mainly biofuels, the types of ethanol production techniques ($PTBE_i$) considered in the tool are from soy and corn; the bioenergy produced must be split between them, and each technique has a unique water tag ($WPBE_i$). The water consumption factor for bioenergy covers production and refining. The total water consumed for bioenergy production (WEPBE) is the summation of energy produced by the technique multiplied by the water consumption factor. Table 5 reflects the notations used and the equation.

$$WEPBE = EPBE \times \sum_{i=1}^{2}(PTBE_i \times WPBE_i)$$

3.3.2. Water for electricity generation

Quantification of water usage, consumption and withdrawal, for the electricity generation portfolio requires two steps after the insertion of the electricity sources data. In the first step, the user identifies the electricity generation percentage in accordance with the type of generator for each source. Almost all electricity generation sources have multiple prime movers, and each has its own withdrawal and consumption factors: it is important to split the source generation per type of generator. In the second step, and after forming the generator portfolio within each source, the user labels the fraction of cooling technology used for each type of generator. Cooling technologies vary within each electricity source: each type of generator and cooling technique has a unique water consumption dynamic. The embedded water consumption and withdrawal factors consider the current overall efficiency of the generators (Table 6).

Should an increase in the overall efficiency of a generator occur, the heat dumped decreases, therefore, fuel input and water used for cooling decrease. Efficiency is inversely proportional to fuel input and water use. Consequently, an increase in efficiency translates into a decrease in input fuel: less heat is dumped, which translates into less water used. EPAT allows the user to multiply the fuel input value by the incremental efficiency increase.

The electricity generation sources are coal, natural gas, nuclear, hydro, wind and solar. Sources are in either of two categories: nonrenewable or renewable. The non-renewables (natural gas, coal, nuclear) require cooling, whereas renewables do not. Electricity from nuclear, hydro, and wind have only one type of production: generic steam, hydro turbine, and wind turbine respectively. Cooling technologies considered are cooling towers, once-through, recirculating reservoirs, and dry cooling. The generator types, cooling technologies and

Table 10
Notations and water factors for wind electricity used in EPAT.

Wind (WI)
WCWI (gal/GJ)
0.1

Table 11
Notations and water factors for hydroelectricity used in EPAT.

Hydroelectric (HY)
WCHY (gal/GJ)
2000

Table 13
Notations and carbon footprints of energy sources used in EPAT.

Energy source	Notation	Carbon footprint (g CO_2/GJ)
Oil	CPOL	9778
Natural gas	CPNG	32,694
Coal	CPCO	8889
Bioenergy	CPBE	36,000

calculation of water footprints for all electricity sources in the tool are discussed below.

3.3.2.1. Natural gas. After inserting the total electricity generated from natural gas sources (EGNG), the first step is splitting this value ($GTNU_i$) among the generator types used. The three generator types are steam (ST), combined cycle (CC), and gas turbine (GT), the main natural gas generator types found in Texas. The constant n_i refers to the number of cooling technologies for each generator type (i): each i has n_i cooling technology options. The cooling technology for each generator type (i) is referred to with the notation j. Step two is identifying the fraction of electricity produced by generator i using cooling technology j ($CTNU_{ij}$). After identifying the total natural gas electricity generation by type of generator types and each generator type by cooling technologies, the product of each is multiplied by its associated water consumption factor ($WCNU_{ij}$). Finally, the total water consumed by natural gas electricity generation (WCGNG) is the summation of water consumed by generators with cooling technologies. Table 7 shows the notations for natural gas generator and cooling types, and the tool equation used to calculate the total water consumed by natural gas electricity.

$$WWGNG = EGNG \times \sum_{i=1}^{3} GTNG_i \sum_{j=1}^{n_i} CTNG_{ij} \times WWNG_{ij}$$

for $\{n_1, n_2, n_3\} = \{4, 2, 1\}$

$$WCGNG = EGNG \times \sum_{i=1}^{3} GTNG_i \sum_{j=1}^{n_i} CTNG_{ij} \times WCNG_{ij}$$

for $\{n_1, n_2, n_3\} = \{4, 2, 1\}$

3.3.2.2. Coal. In the state of Texas, electricity generated from coal is mainly through two technologies: generic steam (ST), and integrated gasification combined cycle (IGCC). To calculate the water needed for the natural gas electricity process, the user splits the total coal electric power generated (EGCO) into fractions representing each type ($GTCO_i$). Then, for each generator i, there are n_i cooling technologies. The next step involves further splitting the electricity generated from i by type of cooling used ($CTCO_{ij}$). The total electricity generated with coal is then multiplied to the product of the fractions, $GTCO_i$ and $CTCO_{ij}$, and then further multiplied with its respective water consumption factor $WCCO_{ij}$. Total water consumed by coal electricity generation (WEGCO) is the summation of products. Table 8 shows coal generator and cooling types with their notations, and the tool equation used to calculate the total water consumed.

$$WWGCO = EGCO \times \sum_{i=1}^{2} GTCO_i \sum_{j=1}^{n_i} CTCO_{ij} \times WCCO_{ij} \quad \text{for } \{n_1, n_2\} = \{3, 1\}$$

$$WCGCO = EGCO \times \sum_{i=1}^{2} GTCO_i \sum_{j=1}^{n_i} CTCO_{ij} \times WCCO_{ij} \quad \text{for } \{n_1, n_2\} = \{3, 1\}$$

Table 12
Notations and water factors for solar electricity used in EPAT.

Solar (SO)		
i	$GTSO_i$	$WCSO_i$ (gal/GJ)
1	PV	0.1
2	CSP	250

3.3.2.3. Nuclear. Unlike previously discussed sources, nuclear sources have only 1 type of generator: the steam turbine (ST). Thus, there is no need to identify a generator portfolio. Nuclear power uses three types of cooling: the user must define their fractions ($CTNU_i$) among the total nuclear power generated (EGNU). Each cooling system has a unique water tag ($WCNU_i$): the summation of the products gives the total water consumed in nuclear power generation (WEGNU). The cooling types, their water tags, notations, and the tool equation used to calculate the total water consumed are shown in Table 9.

$$WEGNU = EGNU \times \sum_{i=1}^{3} CTNU_{ij} \times WWNU_{ij}$$

$$WCGNU = EGNU \times \sum_{i=1}^{3} CTNU_{ij} \times WCNU_{ij}$$

3.3.2.4. Wind. As a renewable electricity source, wind does not directly consume water in its process, nevertheless, wind does have a water consumption factor. Water is consumed when manufacturing and constructing the wind turbines and must be accounted for. The total wind power generated (EGWI) is multiplied by the water factor (WCWI) to obtain the total water consumed by wind power (WEGWI). Table 10 reflects the notations for wind power used in the tool calculations.

$$WEGWI = EGWI \times WCWI$$

3.3.2.5. Hydro. A renewable source of electricity similar to wind, hydropower has only one type of generator: the turbine. Water is consumed through evaporation in the process of hydroelectric generation. To quantify the total water consumed by hydropower (WEGHY), the total inserted hydropower generation (EGHY) is multiplied by the

Table 14
Notations and carbon footprints of electricity sources used in EPAT.

Electricity source	Notation	Carbon footprint (g CO_2/GJ)
Natural gas	CGNG	132,750
Coal	CGCO	246,334
Nuclear	CGNU	5806
Wind	CGWI	8194
Hydro	CGHY	3139
Solar	CGSO	14,833

Table 15
Notations and land use factors of energy sources used in EPAT.

Energy sources	Notation	Land transformation (m^2/GJ)
Oil	LPOL	21
Natural gas	LPNG	31
Coal	LPCO	83
Bioenergy	LPBE	120

Table 17
Notations and spot prices energy sources used in EPAT.

Energy sources	Notation	Spot prices			
Oil	SPOL	50.45	\$/bbl	8.606982489	\$/GJ
Natural gas	SPNG	2.9	\$/MMBtu	2.748815166	\$/GJ
Coal	SPCO	31.83	\$/ton	1.5487	\$/GJ
Ethanol	SPBE	1.49	\$/gal	16.81247028	\$/GJ

water consumption factor (WCHY); notations for hydropower used in the tool calculations are shown in Table 11.

$$WEGHY = EGHY \times WCHY$$

3.3.2.6. Solar. While a renewable source of electricity, solar is different from wind and hydro in that it has two generation types embedded in the tool: photovoltaic (PV) and concentrated solar power (CSP). Photovoltaic does not consume water directly, but like the wind turbine, photovoltaic electricity generation consumes water indirectly. Concentrated solar generation consumes water through both generation and cooling. After inserting the total solar power generated (EGSO), the fraction generated by each type i ($GTSO_i$) must be identified and the generator type fractions are multiplied by their respective water consumption factors ($WCSO_i$). The summation of the product of the fractions and water tags gives the total water consumed by solar power (WEGSO). The notations used in the tool calculations for solar power are shown in Table 12.

$$WEGSO = EGSO \times \sum_{i=1}^{2} GTSO_i \times WCSO_i$$

3.3.3. Emissions

Carbon footprint is an environmental cost associated with energy portfolios. Every energy production and electricity generation activity has a carbon footprint. The quantification of carbon emissions is a must when performing energy planning. To ensure a clean future, understanding the connection between energy portfolios and carbon emissions is vital. Now that climate change is becoming a global issue, huge pressures are placed on nations to pay attention to the carbon dioxide emissions of their energy portfolios. EPAT label the carbon emissions of an energy profile. The volume of carbon dioxide discharged depends on the energy source and the activities associated with production and generation. Each energy source has a unique carbon footprint measure that reflects its lifecycle emissions based on its chemical formation and accompanying processes. The emissions produced by each energy and electricity source are the product of the total energy and electricity of the source and its respective carbon factor.

EPAT considers both direct and indirect contributions of energy portfolios to carbon emissions. Direct contribution is through combustion of energy sources. Indirect contribution is the emission produced by the operational processes. Electricity generated from fossil fuels have a direct impact on the atmosphere: fuel combustion is part of the process. Thus, the carbon footprints of natural gas and coal electricity generation are considered in the calculations. Each fossil fuel electricity source has a unique carbon tag that reflects its direct contribution. EPAT assumes that all energy production and some electricity generation activities produce indirect emissions, since no combustion occurs. The carbon footprints for oil, natural gas and coal energy sources reflect the lifecycle emissions produced in the production, extraction, refining and transporting phases. The electricity generation sources that indirectly impact are nuclear, wind, hydro, and solar. The nuclear energy carbon footprint in the tool reflects the lifecycle emissions of the process by considering the emissions produced in mining, milling, refining and disposal. Although some of these activities might not take place in the studied region, these carbon footprints are somehow imported when generating electricity from nuclear. Wind, hydro and solar are renewable energy sources that do not directly emit carbon dioxide when generating electricity. Nevertheless, these renewable energy sources have an indirect contribution when manufactured and constructed, therefore, their indirect carbon footprint is accounted for in the tool. Bioenergy is a renewable energy source, and, in fact, has a positive effect on the atmosphere by sequestrating the carbon dioxide; however, the production process also has a negative effect on the atmosphere. EPAT considers the indirect emissions of bioenergy. Tables 13 and 14 show the carbon footprint factor for the energy and electricity sources, their notations, and the equation used to quantify the carbon dioxide emissions.

3.3.3.1. Carbon footprint of energy production.

$$CEP = EPOL \times CPOL + EPNG \times CPNG + EPCO \times CPCO + EPBE \times CPBE$$

3.3.3.2. Carbon footprint of electricity generation.

$$\begin{aligned} CEG = {} & EGNG \times CGNG + EGCO \times CGCO + EGNU \times CGNU + EGWI \\ & \times CGWI + EGHY \times CGHY + EGSO \times CGSO \end{aligned}$$

3.3.4. Land

Energy production and electricity generation take up a lot of land. Every constituent of the energy portfolio requires a dedicated piece of land, and makes land availability a constraint for energy portfolios: land may sometimes be considered more crucial than water in energy planning. The customization of an energy portfolio is directly related to the available land. Land is sometimes introduced as an ecological cost accompanying the energy portfolio because every energy activity has an ecological footprint. Moreover, land often competes with the agriculture sector, making land mapping and quantification a condition to any expansion decision. For example, when a policy maker is planning

Table 16
Notations and land use factors of electricity sources used in EPAT.

Electricity sources	Notation	Land transformation (m^2/GJ)
Natural gas	LGNG	2
Coal	LGCO	3
Nuclear	LGNU	13
Wind	LGWI	286
Hydro	LGHY	2778
Solar	LGSO	115

Table 18
Notations and cost of generation of electricity sources used in EPAT.

Electricity sources	Notation	Cost of electricity generation (\$/GJ)
Coal	CECO	1.138
Natural gas	CENG	1.4167
Nuclear	CENU	0.972
Wind	CEWI	1.194
Hydro	CEHY	0.9167
Solar PV	CESO	2.138

Table 19
Scenario 1 - electricity generation portfolio.

Electricity sources (billion kWh)	2015	
	No CPP	%
Natural gas	214	57%
Coal	84	22%
Nuclear	40	11%
Wind	36	9%
Other (solar/hydro)	3	1%

Table 20
Scenario 1 - energy production portfolio.

Energy sources	2015
	Reference
Oil (trillion barrels)	1.148
Natural gas (trillion cubic feet)	8.14
Coal (million short tons)	35
Ethanol (million gallons)	390

to modify the energy portfolio, plans are strictly governed by land availability.

The generation of electricity demands substantial land. Oil, natural gas, and coal production all require onsite mining, extraction, and refining. Mining for oil and gas is a major land user, particularly with the adoption of horizontal drilling. Coal surface and underground mining uses land, and sometimes deteriorates the original formation. Transportation of energy products through pipeline networks is a major land users in the fossil fuel energy sector. Bioenergy is by far the biggest user of land due to crop plantations. Land used in electricity generation is either through on site mining and construction of fossil fuel power plants, or through the development of renewable energy farms and sites. Renewable energy requires significantly more land for electricity generation that conventional fossil fuel sources. Identifying areas of land to be dedicated to energy production and electricity generation while limiting the ecological, economic, and social harm done represents a major challenge to both the policy makers and the energy sector. EPAT quantifies land demands for each proposed energy portfolio scenario. Every energy production source has a respective land footprint, and similarly for electricity generation. The land factors embedded in the tool consider the whole lifecycle of the energy and electricity sources. Land factors used in the calculations, along with its equation are shown in Tables 15 and 16.

3.3.4.1. Land for energy production.

$$LEP = EPOL \times LPOL + EPNG \times LPNG + EPCO \times LPCO + EPBE \times LPBE$$

3.3.4.2. Land for electricity generation.

$$\begin{aligned} LEG = {} & EGNG \times LGNG + EGCO \times LGCO + EGNU \times LGNU + EGWI \times LGWI \\ & + EGHY \times LGHY + EGSO \times LGSO \end{aligned}$$

3.3.5. Economics

Cost is a major parameter to consider when investigating energy portfolios. The total cost of energy production is a function of technology, production costs, capital spending, operational cost, subsidies and gross tax. The cost of energy varies around the world, depending on the geographic location, technology and the global economy. It is neither constant nor independent of externalities. Most nations produce energy to reach self-sufficiency and meet the energy demands of its population and economy. Yet, some nations export energy, making a business of it. Some policy makers favor the maximization of profit over natural resource conservation, arguing that revenue can be considered as a societal and economic label. High revenues translate into more jobs, which translates into societal benefits. Thus, the goals of financial profit, environmental preservation, cost reduction, and social benefit may clash.

The exact cost of energy production is extremely difficult to calculate: first, companies often merge the costs of oil and gas production into a single total figure. Even though production data is split, companies may not separate the costs of oil production from those of natural gas production. Bundling costs masks the individual energy cost of oil and gas; second, the cost of energy production is a combination of multiple financial and economic factors, which makes it complex to calculate. Therefore, for energy production, the spot price of energy sources is used as an economic measure. The exact magnitude of change is less important than the direction of the change, therefore, for energy production, the EPAT uses energy price as a measure of the economics of energy production. The revenues from the energy production portfolio are quantified as a function of spot prices. For coal production, the spot price of lignite coal is considered (assuming all coal production in Texas is lignite). For simplicity, bioenergy refers to ethanol, thus the spot price of ethanol is considered.

Similarly, for electricity generation, the real cost for any electricity generating system is difficult to acquire from normally accessible information. Cost information for technologies with significant historic data are available and include conventional coal power plants, generic

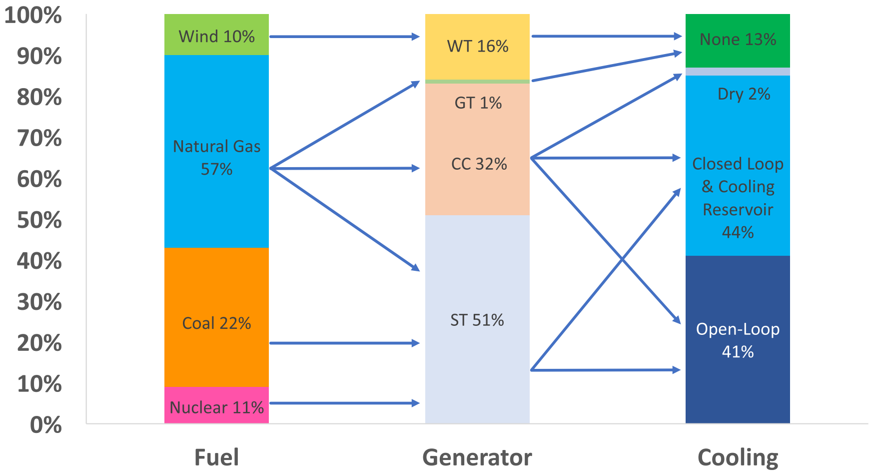

Fig. 2. Relationships between fuel, generator, and cooling system for Texas electricity generation portfolio in 2015.

Table 21
Scenario 2 - electricity generation portfolio (EIA AEO, 2016).

Electricity sources (billion kWh)	2030	
	CPP	%
Natural gas	231	52%
Coal	73	16%
Nuclear	40	9%
Wind	99	25%
Other (solar/hydro)	4	1%

Table 23
Scenario 3 - electricity generation portfolio (EIA AEO, 2016).

Electricity sources (billion kWh)	2030	
	CPP	%
Natural gas	230	51%
Coal	115	26%
Nuclear	40	9%
Wind	60	13%
Other (solar/hydro)	4	1%

nuclear power plants, and older renewable energy technologies. New technologies have not operated long enough to formulate costs covering the life-span of operational and maintenance costs. These new technologies include the natural gas combined cycle, modern nuclear power plants, and emerging renewable energy technologies. Furthermore, the accessible cost data of the new technologies does not reflect the lifecycle cost. Thus, the costs of generation adopted by the tool represent an average of old and new generation costs.

The economic parameter of EPAT considers the $ price/GJ for energy produced and $ cost/GJ of electricity generation. The framework is simplified by calculating revenue for energy production, and cost for electricity generation. These two parameters represent the economic aspect of the portfolio. Tables 17 and 18 offer the spot prices for energy production and costs of electricity generation used in EPAT, as well as the notations and equations used to quantify the revenue and cost.

3.3.5.1. Revenue from energy production.

$$REP = EPOL \times SPOL + EPNG \times SPNG + EPCO \times SPCO + EPBE \times SPBE$$

3.3.5.2. End user cost of electricity generation.

$$\begin{aligned} EGC = {} & EGNG \times CENG + EGCO \times CECO + EGNU \times CENU + EGWI \times CEWI \\ & + EGHY \times CEHY + EGSO \times CESO \end{aligned}$$

3.4. Assumptions and limitations

In this research, some assumptions were set to simplify the complex nature of the problem. These assumptions follow.

- Assessed energy production and electricity generation sources are limited to the studied region and do not include biomass or expanded techniques and technologies.
- Information on water, land, and carbon footprints for the energy sources with technologies and techniques are based on extensive literature review, data from U.S. Energy Information Administration, and national laboratories databases.
- EPAT quantifies the carbon footprint resulting from the energy portfolio as the only indication for environmental impact of a scenario; it does not include environmental impact on water, land, soil, and ecology.
- Relationships between system components are based on empirical data (not process-based).
- EPAT assumes a linear relationship between the energy systems and the assessed tradeoffs.
- EPAT only captures current prices of energy and does not include projections. Moderately, it replicates a given point in time with respect to user defined attributes.
- With the purpose of supporting national sustainable policy development, the scale of the EPAT tool is national or state: it does not consider the global context.
- The financial component in EPAT calculates the cost of electricity generation from a consumer perspective does not account for fluctuations in capital costs due to alterations in portfolios. Unit costs are based on market price data.
- The created scenarios are associated with risks; future work should include a methodology to quantify these risks.
- EPAT, as it stands today (including assumptions and limitations), supports the sustainability of energy development by providing a rapid assessment of tradeoffs.

The analysis aims to present itself as evidence based research for policy making, and offers a path to avoid contradiction and unintended consequences in energy development. The EPAT analysis highlights alarming tradeoffs of given policies and portfolios; it points toward the directions that need extensive addressing. The tool could be sustained with a refined methodology, and detailed data.

4. Texas case study

The state of Texas leads the United States in crude oil and natural gas production, and is the largest generator and consumer of electricity in the country with a share of 12.5% (EIA AEO, 2016). Demographically, the state has the second largest population in the country. Environmentally, Texas has the highest carbon dioxide emissions in the US, and it is anticipated that Texas will experience a 40% water shortfall by 2070 (TWDB - SWP17).

The state's overall energy portfolio is unique in that it features almost all possible energy sources. Given its broad energy portfolio, major federal energy policies affect the energy portfolio of Texas. Current policies practiced in Texas include the Renewable Portfolio Standard (RPS) and the Clean Power Plan (CPP), which primarily target the electricity generation sector. RPS mandates the provision of a minimum amount of generation from renewable energy sources, with a unique target for each state. The CPP mandates reduced carbon dioxide emissions from fossil fuels and extends tax credits for renewable

Table 22
Scenario 2 – energy production portfolio (EIA AEO, 2016).

Energy sources	2030
	Reference
Oil (trillion barrels)	0.975
Natural gas (trillion cubic feet)	12.1
Coal (million short tons)	27
Ethanol (million gallons)	371

Table 24
Scenario 3 – energy production portfolio (EIA AEO, 2016).

Energy sources	2030
	Reference
Oil (trillion barrels)	0.975
Natural gas (trillion cubic feet)	12.1
Coal (million short tons)	27
Ethanol (million gallons)	371

Table 25
Scenario 1 - summary of results for energy production portfolio.

Energy production					
	Oil	Natural gas	Coal	Bioenergy	Total
Energy prod. (M GJ)	7072	9896	609	46	17,623
Water con. (M gal)	103,351	34,177	18,257	9150	164,934
Emissions (M tons)	69	324	5	2	400
Land (km^2)	106	208	24	5545	5883
Revenue (M USD)	$57,917	$23,606	$1114	$581	$83,218

energy, mainly solar and wind. As a result, RPS policy directly impacts the electricity mix, whereas the CPP does so indirectly. Although both policies directly address the electricity generation portfolio, both indirectly affect the energy production portfolio. Texas, then, represents a convenient geographical region to study and assess current and future implications of energy portfolios. The size of Texas is suitable for pilot analysis, yet, due to its large area, results can be extrapolated to a national level. The state also represents a typical case in which policies have huge impact on projected energy portfolios due to its diverse energy production and electricity generation portfolios.

4.1. Scenarios

The water-energy-food nexus approach will be applied to the whole state of Texas, by assessing the sustainability of its current and projected state energy portfolios, and these assessments will be evaluated using EPAT. The portfolios analyzed in this research are provided by the Energy Information Administration (EIA) database. A level of uncertainty exists in every projection process and is related to many variables, including policy, disruptive technology, economic activity, and climate change.

The 2016 EIA Annual Energy Outlook (EIA AEO) projected the energy production and electricity generation of Texas. For energy production, the report presents reference cases for 2015 and 2030. According to the EIA, the projected reference case is the most realistic projection as it considers technological improvement, economic and demographic trends, and current laws and regulations in the energy production sector (EIA AEO, 2016). To avoid uncertainties, this paper considers one projected scenario for energy production: the projected reference case. For electricity generation, the outlook projects the overall Texas electricity portfolio. The paper considers two scenarios for electricity generation: CPP, No-CPP. EIA predicts that EPA's CPP hugely affect the state's electricity mix. Overall, three scenarios are assessed for sustainability: EIA Energy Portfolio Case - 2015, EIA CPP with Energy Reference Case - 2030, and EIA No-CPP with Energy Reference Case - 2030.

4.1.1. Scenario 1 - EIA Energy Portfolio Case – 2015

When projecting energy portfolios and assessing associated impacts, it is essential to have a base scenario. In this research, projected scenarios are compared to the base scenario to enable comparison of observed changes. The table Scenario 1 shows the energy production and electricity generation portfolios for 2015 in Texas. Railroad Commission of Texas (RRC) data for 2015 indicate production of around 1148 billion barrels of oil and 8 trillion cubic feet of natural gas. In this research, it was assumed that 90% of oil came from primary recovery and 10% from EOR; 80% of the produced natural gas from hydraulic fracturing and 20% extracted using conventional techniques (RRC, 2015). The average water reuse of 20% in oil and gas operations was considered. Coal (mainly lignite) and bioenergy (mainly corn-ethanol) are not as popular as oil and gas in Texas: in 2015, 35 million short tons and 390 million gallons were produced respectively (Table 19, NREL, 2017).

Demand for and generation of electricity vary from year to year, as do the generator technologies and cooling systems. As shown in Fig. 2, in 2015, 83% of the power plants used water-based electricity generating and cooling systems. In other words, 51% of power plants operated on the steam cycle (coal, natural gas and nuclear), and 32% operated on the combined cycle (natural gas). The remaining 17% of power generating plants operated on wind and gas turbines that require negligible volumes of water for cooling (only gas turbines).

4.1.2. Scenario 2 – EIA CPP with Energy Reference – 2030

The 2016 Annual Energy Outlook projects energy production rates based on commodity price, prospective technology advancements, and anticipated policies. The referenced scenario, represents the average scenario of all probable outcomes and extremes. According to the Outlook, oil production is set to decrease by 15%, coal production by 23%, and ethanol production by 5%, as a reference case for the year 2030. On the other hand, natural gas production is set to increase by 48%. As an assumption based on feedback from experts, EOR and unconventional natural gas production in Texas are set to increase in the future to become 15% and 90% of the total respectively. Also, as an optimistic conservative assumption going hand in hand with the CPP, an expected water reuse policy of 40% was assumed in this scenario (Table 21).

In the presence of the Clean Power Plan, a big portion of coal electricity generation is retired, leading to increased natural gas and renewable energy generation. Texas is projected to decrease its coal-fired generation capacity by 13% by 2030, reaching 73 billion kWh. This is not surprising, given that Texas is not a coal-dependent state: coal generation already diminished from 34% to 22% between 2014 and 2015. The 15 billion kWh additional capacity from natural gas in 2030 will be generated from the combined cycle technology using the recirculating cooling system. Nuclear power's share of electricity generation is expected to remain constant between 2015 and 2030, at 40 billion kWh. The renewable energy added capacity expected to supply 25%, mainly from wind, with solar supplying the remainder of the electricity portfolio in 2030 and reaching 99 billion kWh. Even with policies encouraging water and environmental conservation, water dependent electricity generation power plants will continue to be dominant, despite expected technological advancements and deployment of renewables.

4.1.3. Scenario 3 – EIA No CPP with Energy Reference – 2030

Similarly, the same projections for oil, natural gas, coal, and ethanol are applied. Unlike Scenario 2, however, Scenario 3 carries a pessimistic assumption of the removal of the CPP; water reuse is assumed to remain at 20% in Scenario 3 (Table 23).

Table 26
Scenario 1 - summary of results for electricity generation portfolio.

Electricity generation							
	Coal	Natural gas	Nuclear	Wind	Hydro	Solar	Total
Elec. gen (M GJ)	302	770	144	130	6	4	1357
Water with. (M gal)	2.1×10^6	1.1×10^6	4.7×10^5	0	∞	0	3,678,518
Water con. (M gal)	22,050	45,511	25,280	13	12,960	0	105,815
Emissions (M tons)	74	102	1	1	0	0	179
Land (km^2)	8	1	2	70	4	1	85
Cost (M USD)	$344	$1091	$140	$155	$6	$9	$1745

Table 27
Scenario 2 - summary of results for energy production portfolio.

Energy production					
	Oil	Natural gas	Coal	Bioenergy	Total
Energy prod. (M GJ)	6011	14,646	456	43	21,157
Water con. (M gal)	92,477	40,790	13,693	8601	155,560
Emissions (M tons)	59	479	4	2	543
Land (km^2)	90	308	18	5213	5628
Revenue (M USD)	\$49,189	\$35,090	\$859	553	\$85,691

If the Clean Power Plan (CPP) is dropped, or if Texas pulls out of the plan, then EIA projects the electricity generation portfolio shown in Scenario 3. Predictably, the electricity generated from coal power plants will increase significantly, 37%, by the year 2030. The absence of regulations governing carbon emissions will pave the way for added coal-fired capacity. Moreover, natural gas electricity generation will increase by 7.5% by 2030. It is assumed that natural gas-fired added capacity are combined cycle power plants with cooling towers. Nuclear power capacity remains constant at 40 billion kWh. Finally, renewable energy is set to witness a very slight increase compared to the CPP case, reaching only 66%. Electricity generation from coal, natural gas, and nuclear will still represent almost 86% of total electricity generation by 2030, keeping thermoelectric power plants dominant in the absence of CPP.

Each scenario was assessed based on the resource requirements and environmental impacts of the energy portfolio. Requirements and impacts assessed were:

- Water footprint (Million gal)
- Carbon footprint (Million ton CO_2)
- Land footprint (km^2)
- Revenue from energy production (Million USD)
- Cost of electricity generation (Million USD)

The results of the three studied scenarios are shown with tables and bar charts indicating resource requirements and environmental impacts of the complete energy portfolio, including water usage, emissions, land use, and the cost or revenue for each energy and electricity source.

5. Results

5.1. Scenario 1 - EIA Energy Portfolio Case – 2015

The most water intensive energy resource is oil: 200 thousand million gallons of water were consumed to produce 1148 billion barrels of oil in 2015. To produce 8.14 trillion cubic feet of natural gas in 2015, 1200 thousand million gallons of water were consumed. Compared to oil and natural gas production, the amount of water consumed by coal and bioenergy is minimal, but if the water consumed per unit of energy is compared to those of oil and natural gas, there is a huge difference. The ratio of water consumed per unit energy for oil and natural gas are 29 gal/GJ, 3.5 gal/GJ, 29 gal/GJ and 198 gal/GJ respectively. Clearly, oil production is the most water consuming energy production process; and bioenergy the least (Table 25).

As for emissions, it was found that natural gas production is the largest carbon dioxide emitting process: 324 tons of CO_2 produced in 2015. The most land demanding energy production process is bioenergy: around 5883 km^2 used in 2015. Natural gas production uses more land than does oil production, nearly double. Finally, even amidst declining oil production, oil still gives the highest revenue: \$58,000 million.

In the electricity sector, the total water withdrawn and consumed in Texas in 2015 was 3,678,518 and 105,815 million gallons, respectively. Thermoelectric plants constituted 90% of the entire electricity portfolio, and used coal, natural gas and nuclear energy sources. Coal-fired power plants withdrew 2,074,382 million gallons of water and consumed only 1% of what was withdrawn: 22,050 million gallons. Natural gas and nuclear were second and third, respectively, in water withdrawal. Around 80% of the natural gas cooling systems are closed-loop systems, which explains why natural gas is the highest water consumer. Natural gas power plants withdrew and consumed 1,132,536 and 45,511 million gallons respectively. Nuclear power uses a generator technology similar to that of coal, steam turbines, and mainly closed loop cooling systems. Although the electricity generated from nuclear is nearly half of that generated from coal sources, the amount of water consumed by nuclear power is almost equal to that consumed by coal. Renewable energy also consumes water, especially hydro. Assuming hydroelectric generation withdraws “infinite” amounts of water, the water consumed reached 13,000 million gallons in generating only 6 million GJ in 2015. Wind and solar electricity generation do not consume water directly in their processes, nevertheless, their lifecycles have a water factor. Compared to the other electricity sources, however, the water consumed by their lifecycles are negligible (Table 26).

Emissions are important byproducts of electricity generation. From Table 20, it is clear that only coal-fired and natural gas-fired electricity are associated with carbon dioxide emissions. Looking at the ton of CO_2 emitted per unit of energy generated, natural gas produces 0.13 tons of carbon dioxide per GJ, whereas coal produces double with 0.26 tons of carbon dioxide per GJ. The impact of coal on carbon emissions is significant: coal's 20% of the electricity generation portfolio is responsible for 40% of the total emissions. The carbon footprints of nuclear, hydro, wind, and solar are negligible: electricity from these sources is generated without fuel combustion. Land is also a factor in electricity generation, most specifically, when it comes to renewable energy. Clearly, renewable energy requires much more land than fossil fuel or nuclear power plants to supply the same capacity. Currently, wind energy accounts for nearly 88% of the total land used for electricity generation, 75 km^2. Coal, natural gas, and nuclear also require land for construction of power plants,

Table 28
Scenario 2 - summary of results for electricity generation portfolio.

Electricity generation							
	Coal	Natural gas	Nuclear	Wind	Hydro	Solar	Total
Elec. gen (M GJ)	263	832	144	356	6	8	1609
Water with. (M gal)	1.3×10^6	5.9×10^5	4.7×10^6	0	0	0	2,363,427
Water con. (M gal)	24,638	47,270	25,280	36	12,960	1	110,184
Emissions (M tons)	65	110	1	3	0	0	179
Land (km^2)	7	1	2	193	4	1	207
Cost (M USD)	\$299	\$1178	\$140	\$426	\$6	\$16	\$2065

Table 29
Scenario 3 - summary of results for energy production portfolio.

Energy production					
	Oil	Natural gas	Coal	Bioenergy	Total
Energy prod. (M GJ)	6011	14,646	456	43	21,157
Water con. (M gal)	109,540	54,386	13,693	8601	186,220
Emissions (M tons)	59	479	4	2	543
Land (km^2)	90	308	18	5213	5628
Revenue (M USD)	$49,189	$35,090	$859	$553	$85,691

cooling systems and other facilities. Finally, yet importantly, is the cost of generation. Taking the ratios of cost per unit of energy, we conclude that nuclear power has the lowest cost of generation, 0.972 $/GJ, followed by coal, 1.138 $/GJ, and wind, 1.194 $/GJ. As a result, from the clean energy preference, nuclear power and wind energy are cheaper sources of electricity compared to natural gas.

5.2. Scenario 2 – EIA CPP with Energy Reference – 2030

This scenario is a conservative energy portfolio projection for the year 2030. It considers the reference case for energy production, with an increase in water reuse, and the CPP for electricity generation. The production decrease of oil, coal, and bioenergy translates into a decrease in total water consumption. Therefore, water consumed by oil, coal, and bioenergy production decrease, even though EOR activities are expected to increase in the future. On the other hand, the total water consumed by natural gas increased. The decrease in water consumed in oil production and the increase in water consumed in natural gas production were not proportional to the change in production because the water reuse percentage increased in 2030. The scenario indicates that, by 2030, there will be policies and regulations that force oil and gas production activities to increase their water reuse percentage, and 40% was the assumed water reuse percentage for the year 2030 (Table 27).

Environmentally, emissions from oil, coal, and bioenergy production will decrease as production activities decline, but emissions resulting from natural gas production activities will increase. Therefore, the total emissions of the energy production portfolio will increase by 2030, with the increase in natural gas emissions being larger than the decrease in all the other energy sources. The total land used by the 2030 energy production portfolio increases with the growing natural gas production activities. While land used by oil, coal and bioenergy decreases, the increase in natural gas activities dominates the total land used, because unconventional gas production increases year by year, and in 2030, 90% of the total produced natural gas will be from unconventional sources. Hydraulic fracturing along with horizontal drilling is used to extract the unconventional natural gas. The total revenue resulting from the projected energy portfolio increases by almost $2000 million, despite the continuing decrease in oil production. The vast increase in natural gas revenue compensates for the reduced revenue from oil production. Nevertheless, the revenues from coal and bioenergy decreased as production decreased (Table 28).

The CPP has a huge impact on the Texas electricity portfolio. As the coal-fired capacity decreases, the total water withdrawn by the electricity portfolio decreases. The total water withdrawn by the electricity portfolio decreased by 1,300,000 million gallons. Coal remains the largest water withdrawing electricity source, even when the capacity is reduced. Nevertheless, the expected stability in nuclear power supply keeps the water withdrawal rates constant, assuming the cooling systems of the power plants remain unchanged. Nuclear accounts for one sixth of the natural gas capacity, yet withdraws a nearly equal volume of water (around 810,000 million gallons). Therefore, nuclear power is an inefficient electricity source when it comes to water withdrawn. Unlike water withdrawal, however, the total water consumed by the portfolio increased by 5000 million gallons.

The goal of the CPP is to shift the electricity portfolio toward clean power, and as observed in the Table 22, total emissions remain constant at 179 million tons, even with the increase in total electricity generation in 2030. If the calculations accounted for carbon capture, the total emissions in 2030 would have been less than in 2015. Nonetheless, this remains a significant advancement, as a 20% capacity increase occurred without increasing emissions. The CPP indirectly encourages renewable energy deployment, and as a result, translates into an increase in land use. In 2030, the total land used by the portfolio increased from 85 to 207 km^2 with renewable energy accounting for 193 km^2 (mainly wind). Finally, clean energy and clean environment come at a financial cost: regardless of the CPP, the cost of electricity generation increased by $250 million as the generation capacity increased (excluding capital cost of the added capacity).

5.3. Scenario 3 – EIA No CPP with Energy Reference – 2030

The scenario considers the same energy production portfolio discussed in Scenario 2, with the assumption that water conserving policies will not be issued, and the current average water reuse factor of 20% remains constant. The only difference in the energy production between the two projected scenarios is the water footprint. In the absence of water policies encouraging water reuse and conservation, and with the expected 48% increase in natural gas production by the year 2030, the energy portfolio water consumption increases by 85,000 million gallons (Table 29).

Unsurprisingly, in the absence of regulations on emissions, coal-fired generation increases. The scenario assumes the same generator technology, steam turbines, still used in coal power plants in 2030. The efficiency of coal turbine is one of the lowest available, therefore increasing coal generation the electricity portfolio is not energy efficient. On the other hand, the scenario assumes that all added capacity from coal and natural gas use closed-loop cooling. Total water withdrawn increases by almost 300,000 million gallons, due to the

Table 30
Scenario 3 - summary of results for electricity generation portfolio.

Electricity generation							
	Coal	Natural gas	Nuclear	Wind	Hydro	Solar	Total
Elec. gen (M GJ)	414	828	144	216	6	8	1616
Water with. (M gal)	2.1×10^6	6.9×10^5	4.7×10^5	0	0	0	3,217,270
Water con. (M gal)	38,813	45,614	25,280	22	12,960	1	122,689
Emissions (M tons)	102	110	1	2	0	0	215
Land (km^2)	10	1	2	117	4	1	135
Cost (M USD)	$471	$1173	$140	$258	$6	$16	$2064

Table 31
Energy portfolio scenario analysis of outputs.

Scenario	1	2	3
Energy prod. (GJ)	17,623	21,157	21,157
Elec. gen. (GJ)	1357	1609	1616
Water with. (elec.) (million gal)	3,678,518	2,363,427	3,217,270
Total water cons. (million gal)	270,749	265,744	308,909
Total emissions (million Tons)	579	722	758
Total land (km^2)	5968	5835	5763
Total energy revenue (million USD)	83,218	85,691	85,691
Total electricity cost (million USD)	$1745	$2065	$2064

coal-fired generation ramping up. Not only does water withdrawal increase, but also the total water consumption increases. Total water consumed also increased by 17,000 million gallons since 2015. Overall, electricity generation's dependence on water increased in a scenario without the CPP (Table 30).

Environmentally, and contrary to the previous scenario, the increase in coal-fired generation led to an increase in total emissions, in this scenario, 215 million tons. Thus, Scenario 3 is neither water efficient nor environmentally friendly. The total land used in this electricity portfolio is less than scenario 2 because the added capacity of renewable energy is less: less land is used in wind and solar farms. Surprisingly, with or without the CPP, the total costs of electricity generation are nearly equal in both scenarios, with Scenario 3 being less by $1 million (excluding capital cost of added capacity). The conclusion is that for almost the same cost of generation, Scenario 3 uses and consumes more water, and produces more carbon emissions.

6. Tradeoff analysis

This section presents an analysis of the sustainability tradeoffs of future energy portfolios in Texas. A comparison between the three scenarios is found in Table 24.

The focus of CPP is decreasing the emissions of the electricity portfolio through adoption of less polluting, cleaner energy, such as natural gas and renewables. As the results show, CPP succeeded in decreasing the total emissions of the electricity portfolio by reshaping the generation mix. Nevertheless, total emissions increased between 2015 and 2030, as the increase in natural gas activities hugely increase emissions. Energy production emits more pollutants to the atmosphere than electricity generation. Therefore, the focus should also be on energy production emissions and not only electricity generation (Table 31).

As observed, in the presence of the CPP, the total water withdrawal of energy portfolio, energy production and electricity generation, decreased from 2015 to 2030. This happened for two main reasons: first, energy production activities decreased in the projected period; second, there was a huge increase in renewables and natural gas electricity generation coupled with a decrease in coal-fired generation. Of course, cooling systems also react to the shifts in the electricity portfolio. In the second scenario, the number of open-loop cooling systems decreased as coal-fired power plants are substituted with natural gas power plants using closed-loop cooling and renewables. This switch from open- to closed-loop decreases the total withdrawn water of the electricity portfolio. Also, the total water consumed by the whole energy portfolio decreased by 5000 million gallons. Nonetheless, while the total amount decreased, the CPP had a negative effect on the water consumed by the electricity portfolio, which increased. Closed-loop cooling systems consume more water than open-loop cooling and CPP has no control over the water used in electricity generation, therefore the added cooling system succeeded in reducing water withdrawal rates, but caused a surge in water consumption. Still, 77% of the electricity portfolio depends on water for generation and cooling. Water dependency is not only unsustainable, but also can be considered as a weak spot in the electricity portfolio making the electricity security vulnerable to any serious climatic changes, such as droughts.

The third scenario illustrated what would happen if Texas drops CPP. Not only do the total emissions increase, but water consumption increases as well. The absence of regulatory actions targeting emissions paved the way to additional coal-fired capacity. Texas is now the largest carbon emitter in the United States, making regulations such as CPP a must. Carbon capture and sequestration (CCS) is another way to decrease carbon emissions. Newly built coal-fired power plants are installing CCS systems to reduce carbon dioxide and toxic byproducts. However, CCS can create additional water challenges, since it can double the water consumption of power plants.

Every transformation has tradeoffs. In this case, land is the major tradeoff: energy production and electricity generation are serious land users. The increase in electricity generation through renewable energy requires a lot of land, and with CPP in practice, renewable energy is set to witness a surge, especially in wind energy. Overall, the expected steep decrease in oil production will dominate land transformation amidst an increase in natural gas production and wind energy generation. As a result, an anticipated oil production decrease leads to a decrease in the total land use for both projected scenarios. The third scenario occupies the least land due to wind energy experiencing a small increase in the absence of CPP. As bioenergy is projected to hold its current expenditure, land used by bioenergy will remain the same in 2030.

Oil production is the energy source with the highest revenue. Yet, the decrease in oil production will be met by a huge increase, almost 48%, in natural gas generation by 2030. This rise in natural gas production counterbalanced the lost oil money, translating into a $2000 million increase in scenarios 2 and 3. While the price of ethanol makes it profitable, especially with the current subsidies, production is expected to remain stable. The current energy infrastructure is not ready for an ethanol revolution, although there are technologies capable of producing ethanol at a really cheap cost. The United States has hit the “blend wall”, which is 10%, and surpassing that amount requires a huge infrastructure transformation: retrofitting cars, transportation, and distribution systems to accept more ethanol feed.

The cost of electricity generation is important when projecting energy portfolios. An increase in demand for electricity will lead to an increase in the total cost of generation. However, the electricity mix plays a big role in setting total costs. As observed, the total generation cost of scenarios 2 and 3 are almost equivalent: Texas could shift to a cleaner electricity portfolio without a big difference in cost compared to an electricity mix dominated by fossil fuel and rich in toxic emissions. Nonetheless, with the expected breakthroughs in renewable energy, especially solar and energy storage, the price of electricity per kWh is expected to drop much further, once technologies prove reliable. Currently, Texas dumps a lot of wind power due to the huge uncertainty in wind activity forecasts. Had there been efficient and economic energy storage technologies, Texas would not have wasted renewable energy. More renewable energy, along with economic and efficient storage, can significantly decrease the cost of generation.

Future conservation and mitigation policies should not be limited by targeting only one system: such a strategy could simultaneously worsen another system. An increase in production means an increase in revenue; an increase in land use for energy means fiercer competition with the agriculture sector. Therefore, priorities should be set regarding sustainable land management verses revenue above all. Agriculture is the largest water user in Texas; its contribution to the economy is far less than that of the energy sector.

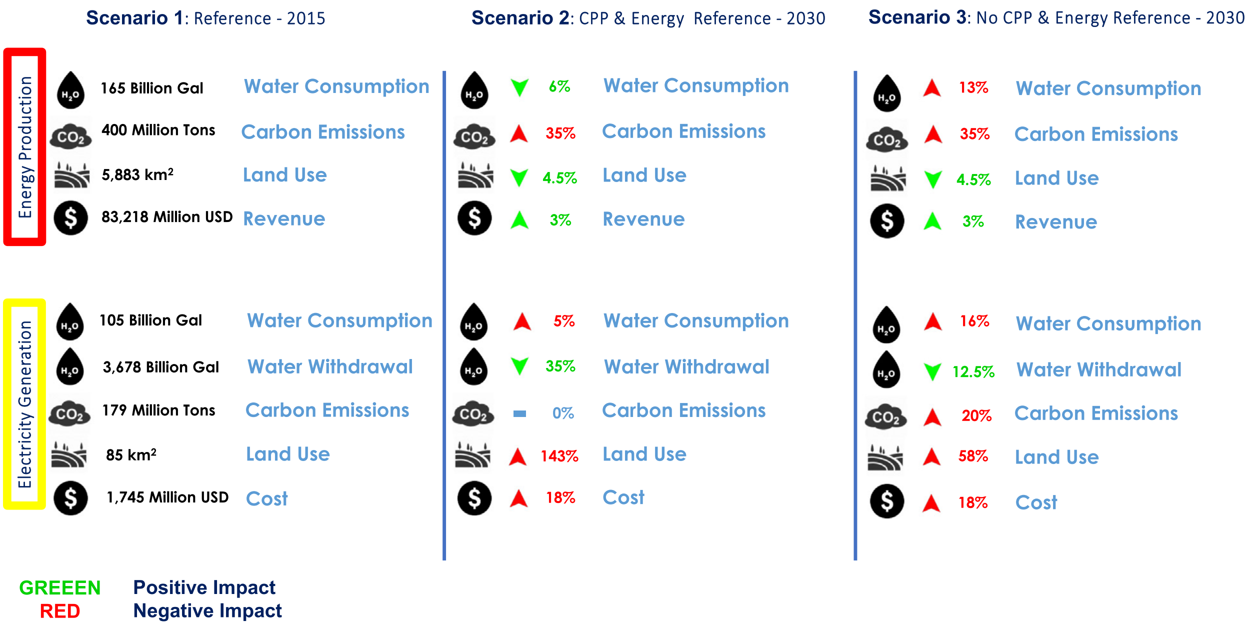

Fig. 3. Tradeoff analysis chart of Texas case study scenarios.

7. Conclusion

Economy and population growth drive the demand intensity of energy, but do not govern the source and supply of energy. Sustainably meeting these demands represents a major challenge (Scott et al., 2011). Energy portfolios are heavily linked with natural resources needed for energy production (extraction, processing and refining) and electricity generation (operation and cooling). The Energy Portfolio Assessment Tool (EPAT) is a holistic nexus tool that links between energy and other systems (water, land, environment, economics, etc.), to measure the impacts of alternative energy portfolios. It is beneficial to a solid foundation for informed, sustainable decision making in energy planning. EPAT enables the user to create energy portfolio scenarios using various energy and electricity sources, which are then evaluated from the perspectives of environmental and economic sustainability.

This research assessed projected energy portfolio scenarios for Texas as set by the U.S. Energy Information Administration: EIA Reference Case – 2015, EIA Clean Power Plan (CPP) & Reference Case - 2030, and EIA No-CPP & Reference Case - 2030. Based on the Texas case study, energy portfolio and policy shifts highly impact water, land, emissions and other systems. Results show that, while CPP succeeds in mitigating carbon emissions and decreasing water withdrawals, it also increases water consumption in electricity generation and significantly increases land use. Yet, in the absence of CPP, carbon footprint surges, as do water withdrawal and consumption. Analysis showed the significance of a supportive water reuse policy in energy production, and the underestimated carbon footprint and land occupation of the energy production lifecycle.

A focus on strategy directed toward supporting clean power generation, water-efficient technologies for energy production and cooling, and capitalizing on water reuse policies in energy production is needed. Similarly, investment in research to increase land productivity when used by energy activities is needed. Such alternatives may not be economically attractive when compared to business-as-usual portfolios, but do hold appeal in the sense of energy resilience, natural resource security, and sustainability. Developing robust energy strategies that mitigate negative tradeoffs and sustain natural resources is critical. To avoid unintended consequences that might result from changing a policy without considering the resultant impacts on other policies, decisions should move from isolated "silos" toward a Nexus systems approach.

Conservation policies should be carefully studied: they sometimes create additional problems even as they may solve others. Water reuse in energy production is directly related to energy consumption and is a key in water conservation. Therefore, new forms of decision making are needed: forms that move away from isolated sector-oriented silos and into acknowledging the systems approach offered by the nexus mentality (Mohtar and Daher, 2016).

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