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# The Energy Transition in New York: A Greenhouse Gas, Net Energy and Life-Cycle Energy Analysis

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**Abstract**

New York state is at the forefront in the USA and also high on the list globally in setting ambitious targets for the transition to renewable electricity, with 70% of generation mandated to be renewable by 2030. The consequences of the associated drastic shift from conventional steam generators to a mix of wind, photovoltaic and hydroelectric (supplemented by pumped hydro storage to ensure dispatchability) is analysed here from the joint points of view of life cycle assessment (LCA) and net energy analysis (NEA). Results indicate that not only is the target effective at drastically reducing the grid mix's carbon emissions and at halving its cumulative demand for imported non-renewable primary energy, but – contrary to often voiced concerns – it is also compatible with sustaining the current level of net energy delivery (after accounting for the energy investments required to deploy and operate all generators).

## 1. Introduction

### 1.1 Background

Climate change is one of the most important challenges facing global society, and yet, despite almost three decades of concerted efforts, there is still no global policy program to address it.

The United Nations Framework Convention on Climate Change (UNFCCC) was created in 1992, and 195 countries joined the original international agreement. UNFCCC negotiations led to the Kyoto Protocol in 1997, which set a target for 37 industrialised countries to reduce their emissions. Continuing UNFCCC negotiations then led to the Paris Agreement in December 2015 (COP21), which shifted the focus to the consequences of carbon emissions, and set the aim to keep global temperatures below two degrees centigrade above pre-industrial levels. However, unlike the earlier Kyoto Protocol, the COP21 is a wholly voluntary agreement, which only encourages – rather than mandates – nationally determined emission targets; also, even this latest effort only involves countries that account for just 55% of global greenhouse gas (GHG) emissions globally.[1] Also at the international level, in 2018 the Intergovernmental Panel on Climate Change (IPCC) published its latest report, which warned that "Global warming is likely to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate",[2] provided estimates for the likely consequences of such temperature increase (including but not limited to sea rise, species extinction and loss of ecosystem services), and calculated the emission reductions required to limit global warming to within such 1.5°C threshold: -45% from 2010 levels by 2030, and then reaching net zero by 2050.[2]

Given that the largest share of anthropogenic greenhouse gas (GHG) emissions are due to the burning of fossil fuels, and that the maximum attainable efficiency of all thermal processes in which such fuels are used is severely – and inescapably – constrained by thermodynamics (Carnot limit), the most effective overarching strategy to simultaneously curb demand for non-renewable primary energy and GHG emissions is pushing for a large-scale switch to electrification across all sectors (including heating and transport), while ensuring that the largest share possible of electricity is produced by renewable, low-carbon technologies (among which, primarily: wind, solar photovoltaics and hydro).[3]

Though there is little doubt that transitioning to renewable energy will lower GHG emissions and reduce overall demand for non-renewable primary energy, there is less known about the impacts the transition may have on the ability of energy systems to maintain current energy surpluses. Murphy (2014) and Carbajales-Dale et al. (2014a) have described how the energy sector must produce energy beyond that required for its own production, called energy surplus or net energy, which can then be used to "pay" for the energy "costs" of a whole range of societal needs, such as infrastructure (e.g. roads, buildings, agricultural systems), or to construct new infrastructure.[4][5]

Energy Return on (Energy) Investment (EROI, sometimes also abbreviated EROEI or ERoEI) is the metric used most often in the literature to determine whether an energy technology provides net energy.[4,6,7,7–20] In general terms, EROI is calculated as the ratio of the Energy delivered ("returned") by an energy system to the total energy invested in the same system in order for it to deliver that energy. Intuitively, an EROI greater than one appears to be a necessary requisite for an energy resource or technology to produce more energy than it consumes, i.e., for it to deliver net energy. However, the devil is in the details, and the literature has often been inconsistent in setting system boundaries, with significant implications on interpretation, as discussed in more detail in Section 3.2.

One concern in the literature is that the EROIs of the main renewable energy technologies may be lower than those of their fossil fuel counterparts, and, as a result, that the energy transition may reduce the overall flow of net energy to society and jeopardize quality of life. However, the bulk of the recent literature does not support this concern, when the various technologies are compared consistently. Raugei and Leccisi (2016) used a life-cycle approach to calculate the EROI of most major renewable and non-renewable electricity generation technologies for the United Kingdom, and their results indicate that, in that country, and when expressing the electricity delivered in terms of its equivalent primary energy (*cf*. Section

3.2), the EROI of silicon-based photovoltaics (PV) is roughly 10 (approximately the same as that of coal-fired electricity in the UK), that of wind is approximately 50 (higher than gas-fired electricity), and that of hydro is the highest of all technologies in the mix at 170 (higher than nuclear).[18] Dale et al. (2012) conducted a meta-analysis of EROI estimates for a variety of technologies, reporting that PV, hydro and wind all invariably had EROIs of over 10 (a significant threshold, as discussed in Section 3.2); similar results for PV were also confirmed in another meta-analysis by Bandhari et al. (2015).[21,22] In fact, the recent literature is now in broad agreement in reporting that the EROI of hydro and wind electricity are well above 10.[6,7,18,19,21] While EROI values below 10 have been reported for PV,[8,23] recent research has found that such low numbers are always due some combination of old data, flawed calculation methods,[20] or inconsistencies in goal and scope definition.[24,25]

Another concern raised in the literature is that the EROIs of variable renewable energy (VRE) technologies, for example photovoltaics and wind power, may be inflated in the literature because they are often calculated without including the costs associated with backup energy storage systems. These storage systems, it is argued, are required to produce electricity when the sun is not shining or the wind is not blowing. The claim is sometimes made that a 1 MW solar array must have a matching 1 MW battery backup system, for example, to provide electricity during the night. This argument stems from the concept that VRE is not “flexible”, in the sense that it cannot be utilized on-demand, or “dispatched”, by the grid operator when needed.

But this argument is misguided. As discussed elsewhere in the literature,[18,19,25] requiring that the EROI of VREs include enough storage to equal the output of the system is inappropriate for at least two reasons. First, by requiring that a VRE technology have an equal amount of power production in storage as a backup system, researchers implicitly switch the goal of the analysis from the estimation of the EROI of an electricity producing technology to the goal of estimating the EROI of a grid system supplied only by that electricity producing technology.[25] Second, to make valid comparisons, e.g. according to the ISO 14044 standard[1],[26] researchers would then also have to estimate similar EROIs for other generation technologies.[18] For example, nuclear and coal generators would require separate “peaking” facilities if they were required to supply electricity for the grid by themselves, as they are notoriously inflexible sources of generation (albeit for opposite reasons, i.e., they must be operated at constant load).

In a previous analysis, Raugei et al. included a grid-level storage component as part of their estimation of the EROI of the Chilean electricity grid, and concluded that moving to a grid with higher wind and PV, with pumped hydro used for storage, would actually increase the EROI of the grid system, notwithstanding the additional investment for and inefficiencies of energy storage.[19]

[1] The ISO 14040 and 14044 standards regulate how a Life Cycle Assessment is to be carried out. In particular, ISO 14040 describes the general principles and framework for LCA, while ISO 14044 further specifies requirements and provides guidelines, including on: definition of the goal and scope, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), interpretation, reporting and critical review, limitations, and conditions for use of value choices and optional elements.

This paper focuses on the prospective evolution of the electricity grid in the state of New York (USA), and it intentionally does so from from a purely bio-physical[2] perspective, with a special focus on energy and greenhouse gas emissions as the key numeraires of interest. In so doing, all economic-induced distortions such as those potentially arising from sector-specific economic incentives, feed-in tariffs, subsidies, discount rates, etc., are completely side-stepped. However, it is also worth mentioning up front that – although economic considerations fall outside the intended scope of this paper – the ongoing sharp declines in unit cost of solar PV, and to a lesser extent wind,[27] also do point to these two renewable technologies as the two most likely candidates for building new generation capacity over the next few decades.

At the federal level in the USA, The Clean Power Plan signed by President Obama in 2015 was a policy to limit GHG emissions from power plants, but with the change to the Trump Presidency, this plan is being challenged and its success is highly uncertain.[28] The lack of federal (and indeed global) support for climate change policies has left a void which, in the United States, is being filled by state-level policies. A number of states within the USA are decreasing GHG emissions by transitioning electricity production to renewable technologies. For example, California is targeting 60% renewable electricity production by 2030; Massachusetts is targeting 40% by 2030; Vermont is targeting 75% by 2032; and the District of Columbia is targeting 100% by 2032.

New York issued a Clean Energy Standard (CES) in 2015 that required 50% of the generation in the state to be renewably-sourced by 2030 (NYS 2016).[29] More recently, New York's CES was amended by Senate Bill 6599 (S6599), which now requires 70% renewable energy generation by 2030, and 100% by 2040.[30] In this analysis, storage is also included as part of the analysis of the entire grid, because S6599 has mandated that storage be built by 2030.[30] As such, bill's state storage capacity target is used to estimate the actual energy storage requirement for the system, and by calculating storage at the grid level, the issue of arbitrarily assigning that storage component to a specific generation technology is avoided.

## 1.2 Objectives of this analysis

Due to the inherent geographical nature of renewable energy, it is important to calculate EROIs for the same technologies in different areas, as the sun shines and the wind blows differently throughout the world. It is also important to analyze other energy metrics in addition to EROI, as they each indicate something different about the energy system. EROI, for example, indicates nothing about the type of energy consumed. Non-renewable Cumulative Energy Demand (nr-CED), on the other hand, indicates how dependent an energy system is on non-renewable primary energy flows, i.e., fossil and fissile energy inputs.

Focusing on New York in particular, the energy transition will also change energy imports and exports from the state. New York does not produce fossil fuels or uranium, so currently each steam generator must import its primary energy source from outside the state. For New York,

[2] The term "bio-physical" refers to a reading of techno-economic processes that eschews conventional economic numeraires and instead seeks to describe and explain their operation making exclusive use of physical units such as kg, MJ, etc. and their derivatives.

then, transitioning to renewable electricity means not only lower GHG emissions and reduced depletion of non-renewable energy resource stocks, but also a concomitant reduction in dependence on out-of-state energy products.

Given these considerations, the objectives of this analysis are to examine how the energy transition envisioned in S6599 will change the net energy, life-cycle energy and GHG metrics of electricity generated in New York. Specifically, we aim to do the following, for both the current (2018) and future (2030) New York grid mix, the latter assuming completion of S6599 and including energy storage:

1) Calculate EROIs and net-to-gross (NTG) energy ratios (*cf.* Chapter 3.2) for all major generation technologies and for the overall grid mix, to estimate the expected change in availability of net energy;
2) Calculate non-renewable cumulative energy demand (nr-CED) for the overall grid mix, to estimate how New York's dependence on out-of-state fossil and fissile energy is expected to change;
3) Calculate total greenhouse gas emissions (global warming potential, GWP) per kWh generated by the grid mix, to estimate the degree of electricity decarbonization that may be expected to be afforded by the successful completion of S6599.

## 2. Current and projected electricity generation and grid status in New York

The electric grid of New York is managed by the New York Independent System Operator (NYISO), which subdivides the state into eleven zones, with interconnection to Pennsylvania-New Jersey-Maryland (PJM) in the south, Independent System Operator New England (ISO-NE) in the east, Independent Electricity System Operator (IESO) in the west, and Hydro-Quebec (H-Q) in the north. The NYISO runs the wholesale market for the state and acts as the balancing authority. The percentage of electricity that is imported from out of state varies from year to year, but it is generally very small (between 2% and 10% of the total NYISO supply).[31]

Since the NYISO operates in the state of New York, the policies written for New York, such as S6599, will impact only the NYISO directly. In particular, Bill S6599 explicitly mandates 70% renewable generation in-state, which is what the present analysis focuses on. However, interestingly, the same Bill also mandates that "no later than two years after the effective date of this article, and each year thereafter, the department shall issue a report on statewide greenhouse gas emissions" and then it explicitly states that "the statewide greenhouse gas emissions report shall also include an estimate of greenhouse gas emissions associated with the generation of imported electricity and with the extraction and transmission of fossil fuels imported into the state which shall be counted as part of the statewide total". This appears to have the intent of pre-emptively avoiding the establishment of a loophole whereby carbon-intensive non-renewable electricity would be imported to supplement the renewable electricity generated in-state.

New York State produced over 130 TWh of electricity in 2018 from generating facilities that fall into one of ten categories (Table 1). Figure 1 then synthesizes the same data after discarding those technologies that output less than 1% of the total. The top five generating categories account for 95% of the generation in the state, with nuclear being the single largest category at 32%. Combined cycle facilities (natural gas) account for nearly the same amount (31%), and hydropower accounts for 23% of the generation. The existing legislation is requiring a buildout of wind and PV, which currently produce only 3% and 0.04%, respectively, of the net generation in the state.

- Table 1 HERE -

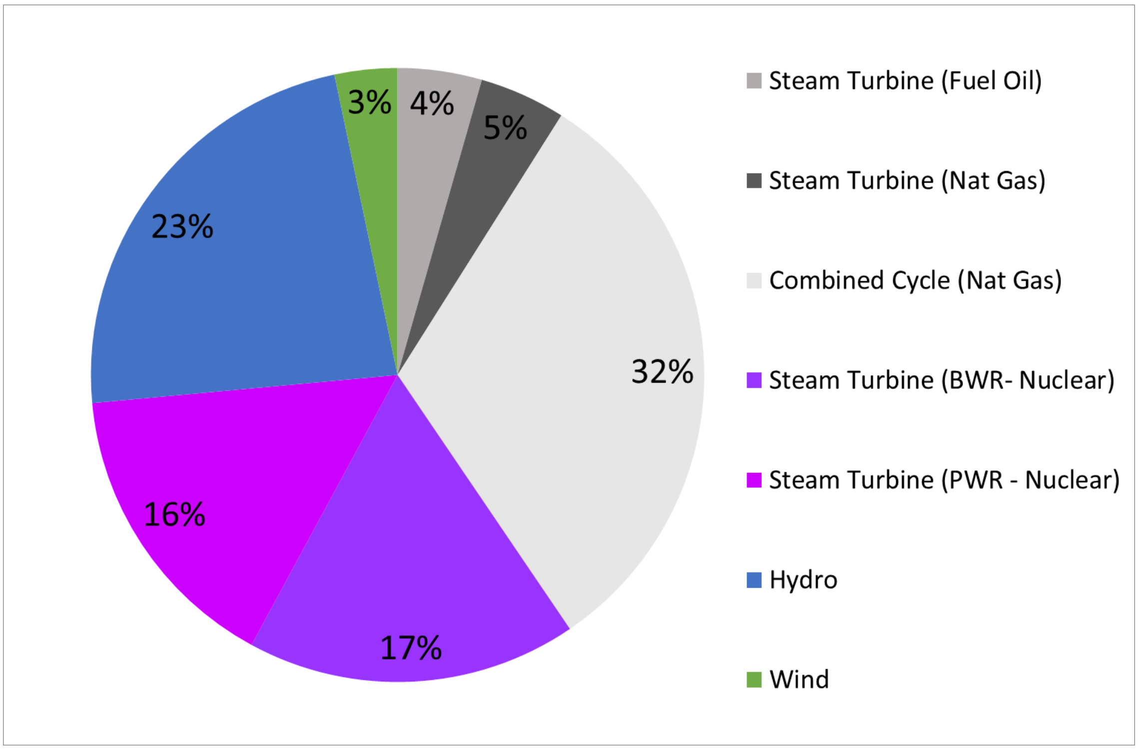


**Figure 1.** Shares of total net (i.e., delivered) electricity generation in New York state (2018).

The New York State Clean Energy Standard, first adopted in 2016 was one of the most progressive renewable energy policies in the United States. In its original form, it called for 50% renewable generation by 2030. In 2019, New York Senate Bill S6599 amended some of the provisions within the Clean Energy Standard, accelerating the adoption of renewable energy by requiring 70% renewable electricity generation by 2030, and 100% by 2040. This bill also specifically mandated the installation of 6 GW of distributed solar by 2025, 3 GW of energy storage by 2030, and 9 GW of offshore wind by 2035.

The New York State Energy Research and Development Authority (NYSERDA) estimated both the bounded technical potential (BTP) and the economic potential for all major renewable energy resources within the state (Table 2). The bounded technical potential is defined as a measurement "of what theoretically would be possible if cost were not a factor" (NYSERDA 2014). The economic potential is the fraction of the BTP where the social benefits are estimated to exceed the avoided costs (NYSERDA 2014).[32] The results from the NYSERDA forecasts are interesting because only PV is forecasted to have enough economic resource to meet the requirements in S6599. Offshore wind has only 6.4 GW of BTP according to the NYSERDA analysis, yet S6599 mandates the development of 9 GW of offshore capacity by 2035. PV, on the other hand, has roughly 10 GW of new economic capacity available, which is much greater than the 3 GW by 2025 required under S6599.

- Table 2 HERE -

Despite this discrepancy, for the sake of this analysis, we shall assume that the resource is available, and calculate all energy and emission indicators (GWP, nr-CED and EROI / NTG) assuming the full buildout is accomplished by 2030 in accordance with the specific S6599 legislation targets for PV, wind and energy storage.

Gross yearly electricity output from wind and PV generators is estimated here by applying their current capacity factors (CFs)[3] - respectively 26% and 14% - to the respective total target installed power figures (the latter being equal to the current installed capacities plus those mandated by Bill S6599 for new installations).

Hydroelectricity production is sized so as to complement wind and PV to meet the 70% renewable gross generation target; also, all 3GW of mandated new energy storage capacity for 2030 is assumed to be Pumped Hydro Storage (PHS), and approximately 10% of the total 2030 gross electricity production (i.e., 15,000 GWh/yr) is assumed to be routed into storage. These twin assumptions are based on two considerations: (i) the proximity and interconnection to the Hydro-Quebec grid (which has ample dammed hydro reservoirs), and (ii) PHS being by far the least expensive and most widespread storage technology at present [33].

Gross electricity output projections for the non-renewable technologies in the 2030 mix are arrived at as follows.

Two nuclear power plants (both of the Pressurized Water Reactor type) in NY state are scheduled for decommissioning soon; these are: Indian Pt2 (1,018 MW), closing in 2020; and Indian Pt3 (1,037 MW), closing in 2021. The 2030 grid mix scenario takes into account these planned closures by scaling the current nuclear electricity generation figures proportionally to the expected remaining nuclear power capacity in 2030, i.e., assuming the CFs of nuclear generators to remain the same as in 2018.

Conventional fossil fuel steam turbines, being the most carbon-intensive technologies in the current mix, are assumed to be phased out completely.

Finally, natural gas combined cycle (NGCC) output is sized so as to balance out the total gross electricity demand, the latter back-calculated from the net demand figure of 140,992 GWh

[3] CFs are defined as the ratio of the average effective power output to the nominal installed power.

projected in the Clean Energy Standard documentation (which includes additional load by from electric vehicles and geothermal heat pumps),[29] after duly taking into consideration the energy losses caused by the inefficiency of the energy storage loop (*cf*. Section 3.2). These calculations indicate that no new NGCC capacity is called for in the 2030 scenario. The already existing power plants are already more than capable of supplying the relatively small share of grid mix electricity required.

The resulting projected composition of the New York grid mix in the year 2030 (gross output, i.e., pre-storage) is illustrated in Figure 2.

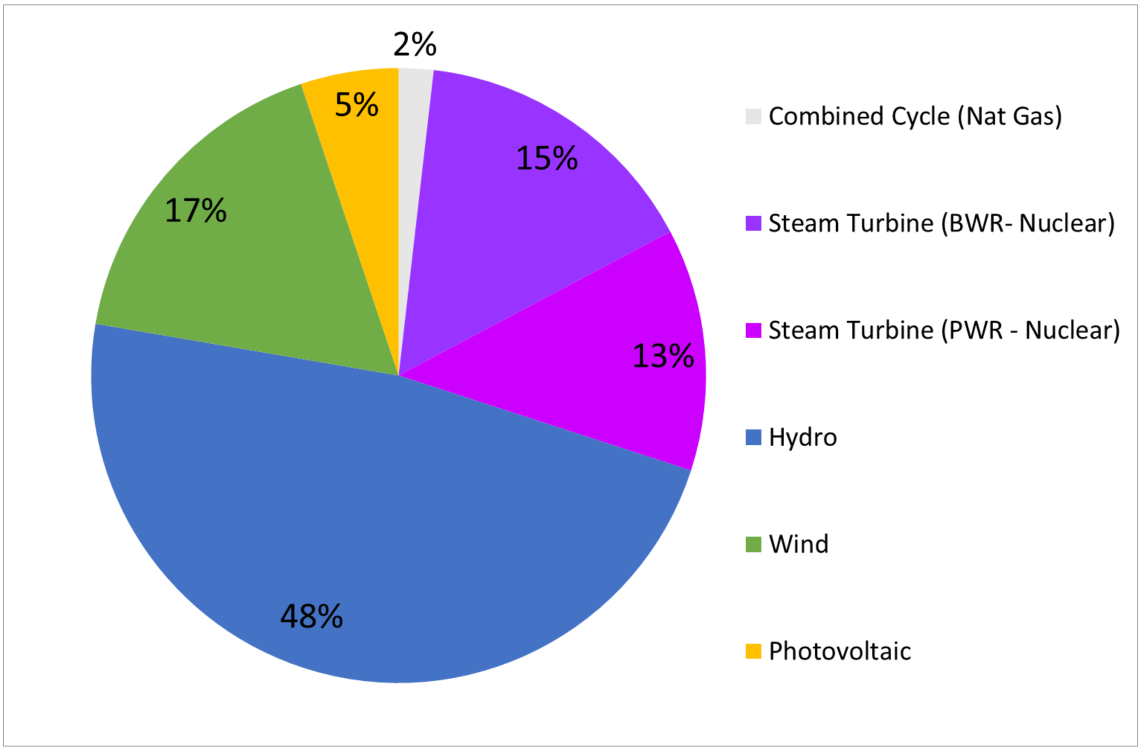


**Figure 2.** Projected shares of total gross (i.e., pre-storage) electricity generation in New York state (2030).

Given the inevitable uncertainties entailed by all medium-term future projections, a few closing considerations are in order.

Historical records so far point to reliable availability of hydro power in the New York and Quebec regions; this provides reassurance that the target values of hydro and PHS capacities will be achieved. Also, the assumed PHS capacity is generous (in fact, it could be considered a "worst case" assumption from the point of view of its negative effect on the calculated energy and emission indicators), and it is deemed sufficient to reduce the risk of failing to meet the electricity demand, despite increased reliance on VRE.

Notwithstanding, unexpected (possibly climate change-induced) extreme weather events could potentially affect the viability of the considered 2030 scenarios; however, addressing these is beyond the intended scope of the present paper.

## 3. Methods

From a methodological perspective, this paper adopts a still relatively novel, fully integrated approach whereby Net Energy Analysis (NEA) and Life Cycle Assessment (LCA) are applied in parallel in a fully coherent way, based on a common inventory analysis. This allows a balanced discussion of the possible trade-offs entailed by the considered energy transition strategy, in terms of carbon emissions (as measured by the GWP indicator), *vs.* user-side effectiveness in energy extraction and delivery (as measured by the EROI and NTG energy ratios), *vs.* long-term energy sustainability and sovereignty (as measured by the nr-CED indicator).

### 3.1. Inventory Analysis

All life-cycle input and output inventory data for the individual technologies analysed here were sourced from the reputable Ecoinvent 3.5 life cycle inventory database.[34]

The following specific processes were selected, all relative to the Northeast Power Coordinating Council (NPCC), of which NYISO is in compliance: “electricity production, hard coal”; “electricity production, oil”; “electricity production, natural gas, combined cycle”; “electricity production, nuclear, pressure water reactor”; “electricity production, nuclear, boiling water reactor”; “electricity production, hydro, reservoir”; “electricity production, wind, 1-3MW, onshore”; “electricity production, wind, >3MW, offshore”. Given the still rapid pace of technological improvement specifically for PVs, the inventory and efficiency estimates for crystalline silicon PV in 2030 were adjusted from the present data based on linear extrapolations informed by a recent IEA report.[35] Also, Bill S6599 mentions a target of “six gigawatts of distributed solar energy capacity”, but does not specify the share thereof that is to be rooftop-mounted *vs*. ground-mounted. In our calculations, we assumed the latter, since it tends to be the more energy-efficient installation type on a large scale (the differences per kWh of generated electricity are however minor).

In lack of region-specific data on the actual material and energy demands associated to the construction of high-voltage transmission lines in the NPCC area, the corresponding “rest of the world” Ecoinvent process for “transmission network construction, long-distance” was used to estimate the associated energy investment (used for EROI and nr-CED calculations) and greenhouse gas emissions (used for GWP calculations). Finally, PHS was assessed on the basis of the same inventory as for “electricity production, hydro, reservoir”, while excluding the electricity used to pump water into storage in order to avoid double-counting, since all the necessary material and primary energy inputs for the generation of that same amount of electricity are already included in the cumulative material and primary energy requirements for the total gross (i.e., pre-storage) electricity generation by the grid mix.

### 3.2. Net Energy Analysis

For the sake of consistency and completeness, the denominator of the EROI ratio for an energy resource is typically quantified as the cumulative primary energy extracted from nature in order to provide the required energy investments for its exploitation up to a predefined stage of its supply chain (e.g., for a petroleum supply chain, such stage may be the wellhead, the refinery gate, or the electricity bus bar). The EROI numerator is often taken directly as the measured amount of energy carrier delivered at that same stage (e.g., respectively, crude oil, refined fuel, or electricity). However, a unit of raw primary energy is not functionally equivalent to a unit of final energy carrier, and "if the numerator and denominator are not measured by the same rule, one loses the intuitively appealing interpretation that EROI > 1 is the absolute minimum requirement a resource must meet in order to constitute a net energy source".[36]

One way of retaining the meaningfulness of the EROI > 1 requirement is to express the numerator, too, in terms of "equivalent" primary energy, applying a substitution logic akin to that commonly employed in Life Cycle Assessment (LCA), whereby one unit of delivered energy carrier is considered equivalent to *x* units of primary energy, based on the cumulative primary energy demand (CED) of the average mix of technologies that is currently used to produce that same carrier. For instance, in the case of electricity, this leads to the definition of $EROI_{PE\text{-}eq}$ as per equation 1:[18]

*Eq. 1)* $EROI_{PE\text{-}eq} = (Out_{el} / \eta_G) / Inv = Out_{PE\text{-}eq} / Inv$

Where:

$EROI_{PE\text{-}eq}$ = EROI (primary energy equivalent output)

$Out_{el}$ = total electrical energy delivered over the analysed system's lifetime

$\eta_G$ = life-cycle primary energy efficiency of the electricity grid mix into which the analysed system is embedded

$Out_{PE\text{-}eq} = (Out_{el} / \eta_G)$ = total equivalent primary energy delivered over the analysed system's lifetime

Inv = sum of all the energy investments required by the analysed system

But even an $EROI_{PE\text{-}eq}$ greater than one does not necessarily mean that an energy resource or technology is providing *enough* net energy for a modern society. As societies become more advanced, they tend to have greater energy demand, and therefore the energy sector must produce more net energy to simply maintain society.[4] Early efforts in this area claimed that an EROI of 3 was the minimum for modern society,[11] while a more recent, and more comprehensive, analysis in this area tentatively put that number at 10.[37]

But, assuming a specific number for the "minimum" EROI supposedly required to support a modern society is intrinsically fraught with complications and always entails a degree of arbitrariness, because any such minimum value is in fact also indirectly determined by the efficiency at which the delivered energy carriers are ultimately utilized and converted into useful work (clearly, less net energy would suffice if it could be used more efficiently). The problem is compounded by the fact that, while for the most part of the modern industrial era the vast majority of the energy transformations have relied on thermal processes – the maximum efficiency of all of which is similarly constrained by the Carnot ratio ($\eta_{max} = 1 - T_C/T_H$) – the world is now on the verge of a major transition to more and more widespread use of electricity as the energy carrier of choice,[3] with potentially far-reaching consequences on the minimum amount of net energy required in the future.[38,39]

Instead, a different approach to estimating whether any specific EROI value may be regarded a significant threshold to be mindful of is that provided by the analysis of its relation to the net-to-gross (NTG) energy ratio. The NTG energy ratio indicates the amount of net energy delivered as a relative share of the gross energy output, according to equation 2:

*Eq. 2)* $NTG = (Out_{PE\text{-}eq} - Inv) / Out_{PE\text{-}eq}$

It can easily be shown that $NTG = 1 - 1/EROI_{PE\text{-}eq}$, and in fact, when plotted against $EROI_{PE\text{-}eq}$, the NTG ratio shows a markedly non-linear decay as $EROI_{PE\text{-}eq}$ declines below approximately 10 (Figure 3). Such trend has been referred to as the "net energy cliff".[4,7,18]

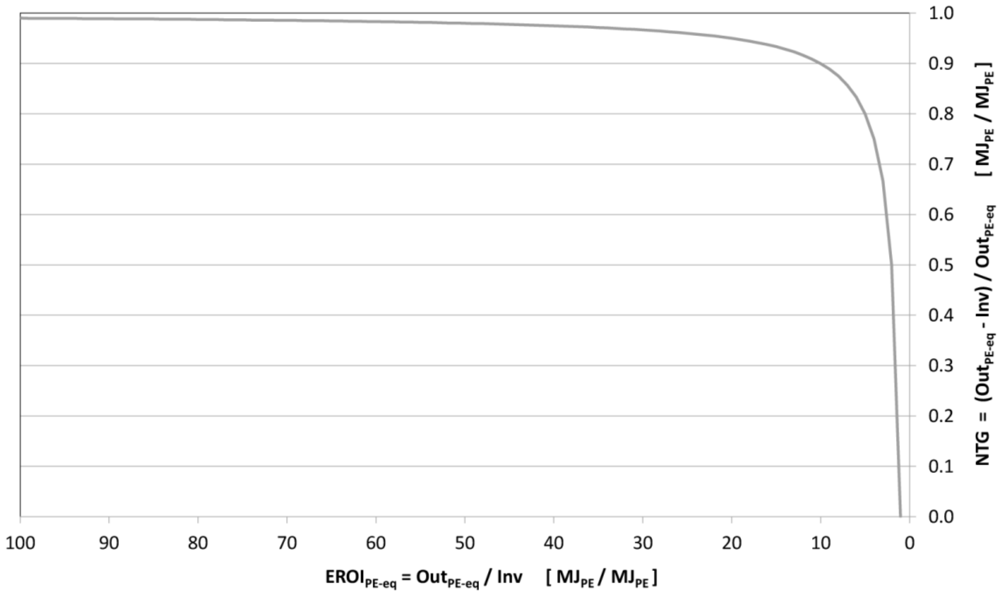


**Figure 3.** Net Energy Cliff diagram displaying the relation between EROI and NTG ratio.

The conclusions from the net energy cliff diagram are clear: net energy flows increase only marginally as EROIs increase beyond 10, whereas they decrease very quickly as EROIs decline below 10.[4]

Finally, from a methodological perspective, it should be noted that the EROI of a mix of technologies that are used together to deliver a common energy carrier cannot be calculated simply as the weighted average of the EROI of the individual technologies that comprise it. This is quickly demonstrated by considering the ideal simplified case in which two technologies, respectively A with $EROI_A = 1$ and B with $EROI_B = 100$, are combined in equal shares to produce one unit of output. By simply taking $EROI_{mix} = 0.5 \times EROI_A + 0.5 \times EROI_B$, one would obtain $EROI_{mix} = 50.5$, which, as is demonstrated below, would be a massive overestimation. Instead, the correct calculation approach starts from the consideration that, in order to produce one unit of output, technology A requires $1/EROI_A$ = 1 unit of energy investment, while technology B requires $1/EROI_B$ = 0.01 units of energy investment. Therefore, the 50/50 mix of the two technologies will require (0.5 x 1 + 0.5 x 0.01) = 0.5005 units of energy investment per unit of total output, resulting in $EROI_{mix}$ = 1/.5005 = 1.998 ≈ 2.

Coming back to the NY grid mix, its overall EROI (primary energy equivalent) may therefore be calculated in the same manner. Additionally, the effect of energy storage also needs to be taken into account. In terms of EROI, storage systems act as a drain on the energy output. Specifically, PHS systems typically have round-trip efficiencies of roughly 80% (Center for Sustainable Systems, 2018),[33] meaning that 80% of the energy routed into the storage system is eventually returned to the electric grid when it is needed.

In light of the above, and consistently with and expanding on previous work,[19] in order to calculate the $EROI_{PE\text{-}eq}$ of the NY grid mix, we used equation 3:

*Eq. 3)* $EROI_{PE\text{-}eq,G} = [1 - s\cdot(1-\eta_S)] / [\ \Sigma_i (\omega_i / EROI_{PE\text{-}eq,i}) + s\cdot Inv_S]$

Where:

$EROI_{PE\text{-}eq,G}$ = EROI (primary energy equivalent output) of the grid mix, incl. storage

s = share of total gross (pre-storage) grid electricity output that is routed into energy storage

$\eta_S$ = round-trip efficiency of energy storage

$\omega_i$ = share of technology i in the gross (pre-storage) grid mix output

$EROI_{PE\text{-}eq,i}$ = EROI (primary energy equivalent output) of technology i

$Inv_S$ = additional primary energy investment per unit of energy routed into storage

### 3.3. Life-cycle Energy Analysis

Life Cycle Assessment (LCA), and specifically life-cycle energy analysis, provides a different – and complementary – viewpoint to that offered by Net Energy Analysis: whereas the latter focuses on how effectively energy resources are exploited, in terms of providing a surplus of net energy per unit of energy invested in the supply chain, LCA's energy metrics are geared towards assessing long-term energy sustainability. Specifically, a key energy demand metric in LCA measures the total non-renewable primary energy that is harvested per unit of output over a system's full life cycle, therein including the actual resource flow being harvested and processed.[40,41] For electricity generation systems, this is calculated as per equation 4:

*Eq. 4)* $nr\text{-}CED = (PE_{nr}+Inv_{nr})/Out_{el}$

Where:

nr-CED = non-renewable cumulative primary energy demand (per unit of output)

$PE_{nr}$ = total non-renewable primary energy directly harvested from nature over the analysed system's lifetime

$Inv_{nr}$ = non-renewable share of all the energy investments required by the analysed system

$Out_{el}$ = total electrical energy delivered over the analysed system's lifetime

The nr-CED of the entire grid mix, including storage, is calculated using equation 5:

*Eq. 5)* $\text{nr-CED}_{,G} = \{1/[1 - s\cdot(1-\eta_S)]\} / [\ \Sigma_i\ (\omega_i \cdot \text{nr-CED}_{,i}) + s\cdot Inv_S]$

Where:

$\text{nr-CED}_{,G}$ = non-renewable cumulative primary energy demand of the grid mix, incl. storage

s = share of total gross (pre-storage) grid electricity output that is routed into energy storage

$\eta_S$ = round-trip efficiency of energy storage

$\omega_i$ = share of technology i in the gross (pre-storage) grid mix output

$\text{nr-CED}_{,i}$ = non-renewable cumulative primary energy demand of technology i

$Inv_S$ = additional primary energy investment per unit of energy routed into storage (assumed 100% non-renewable)

It is noteworthy that for those systems located in geographical regions that are devoid of local non-renewable resource deposits, like New York, the nr-CED metric is also a valuable proxy indicator of energy sovereignty and independence.

### 3.4. Greenhouse gas emission analysis

In order to accurately assess the carbon intensity of electricity generation on the full life-cycle scale (thereby including not only the $CO_2$ emitted directly by the power plants during operation, but also all the greenhouse gases emitted along the multiple supply chains that are required to build, maintain and operate the power plants and all other components of the electricity grid), a LCA approach is adopted here, informed by the life-cycle inventory data discussed in Section 3.1 and complemented by suitable IPCC-derived characterization factors.[42]

## 4. Results and Discussion

As shown in Figure 4, the first noteworthy result of our analysis is that achieving a grid mix that produces 70% of its output with renewable generators by 2030, as stipulated in S6599, will reduce its total greenhouse gas emissions (over the full life cycle of all its components) to 0.021 kg ($CO_2$-eq) per kWh, from 0.27 kg ($CO_2$-eq) per kWh in 2018, i.e., a reduction of 92%. The total GHG emissions in 2030 under this scenario are projected to be 3.02 x $10^6$ tonnes $CO_2$-eq, a 91% reduction from 2018 levels. *The extent of these emission reductions indicates that, from a climate perspective, the newly established renewable targets are very effective.*

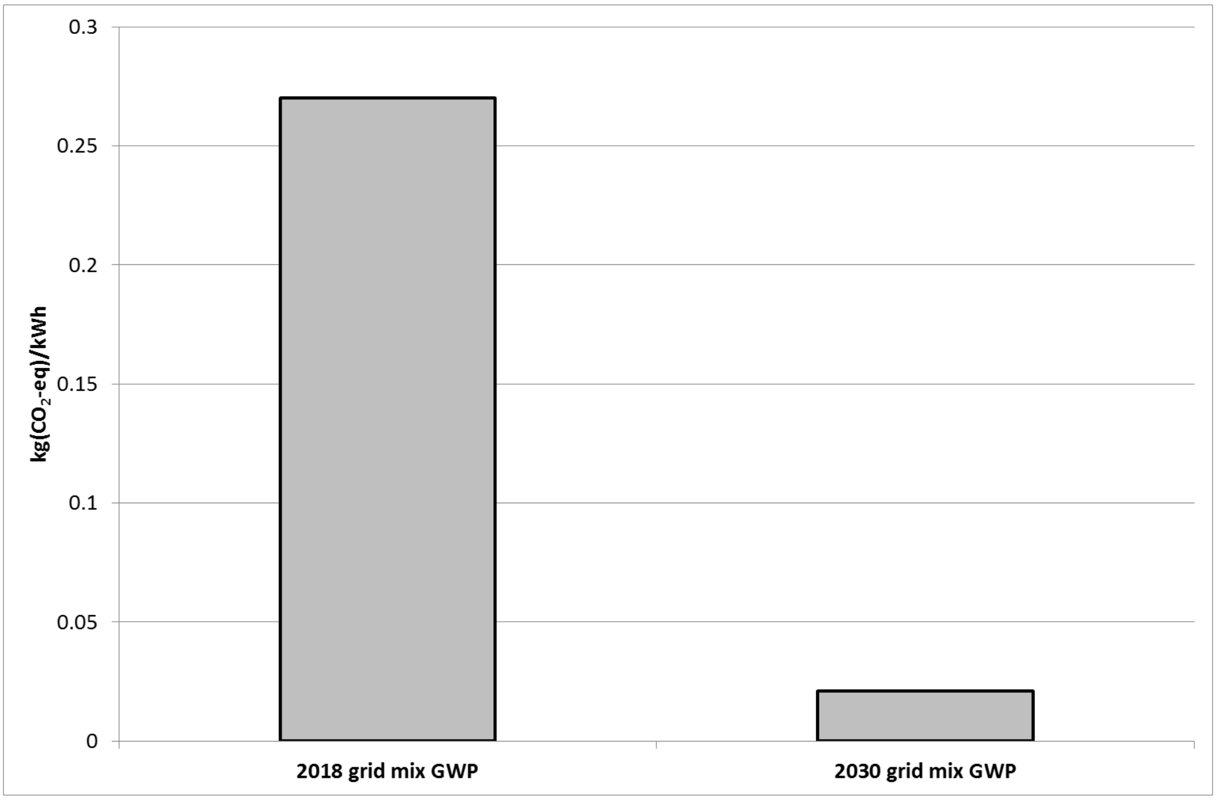


**Figure 4.** Global Warming Potential (GWP) of 1 kWh of electricity produced by the New York grid mix in 2018 and in 2030.

The net energy analysis and life-cycle energy analysis results are presented and discussed jointly, in order to better highlight any trade-offs that the planned energy transition for New York may entail. In Figure 5, nr-CED is measured along the horizontal axis, from right to left, while NTG is measured along the vertical axis, with a reduced scale limited to the range of interest from 0.9 to 1.0 (corresponding to $EROI_{PE\text{-}eq}$ values above 10 – *cf.* Figure 3). The performance of the individual electricity generation technologies is indicated by diamond symbols on the Cartesian plane thus defined (black/solid symbols for 2018 and red/hollow symbols for 2030), with the symbol areas proportional to the respective shares of total electricity production. The overall nr-CED and NTG of the entire NY grid mix are indicated by vertical and horizontal lines (black/continuous lines for 2018 and red/dashed lines for 2030), respectively. In this way, the two quadrants to the right of the vertical grid mix line contain those technologies whose demand for non-renewable primary energy per unit of delivered electricity is lower than that of the NY grid as a whole. Similarly, the two upper quadrants above the horizontal grid mix line contain those technologies that provide a larger unit energy surplus (higher NTG) than average for the NY grid mix. Finally, arrows are superimposed on the chart to better highlight the main changes in symbol and line positioning and/or symbol size from 2018 to 2030.

Overall, our results for New York show that, unsurprisingly, all renewable energy technologies (hydro, wind and PV) are characterized by one order-of-magnitude lower demand for non-renewable energy, over their full life cycle, than conventional thermal technologies (steam turbines, combined cycles and nuclear reactors).

In terms of net energy, instead, the technology-specific results are less clear-cut. At present (year 2018), hydroelectricity is the best-performing technology of all (NTG = 0.99), followed by gas combined cycles and nuclear (NTG = 0.98), and wind and conventional gas steam turbines (NTG = 0.97), in that order. Finally, conventional steam turbines operating on fuel oil are at the tail end (and off the chart) at NTG = 0.84. For the future (2030), the NTG results vary slightly due to the indicator's dependence on the overall life-cycle efficiency of the grid mix ($\eta_G$), which increases from 0.52 in 2018 to 0.70 in 2030. The overall ranking of the individual technologies is however similar, from hydro (NTG = 0.99), to nuclear (NTG = 0.97), to wind (NTG = 0.96), to PV (NTG = 0.93).

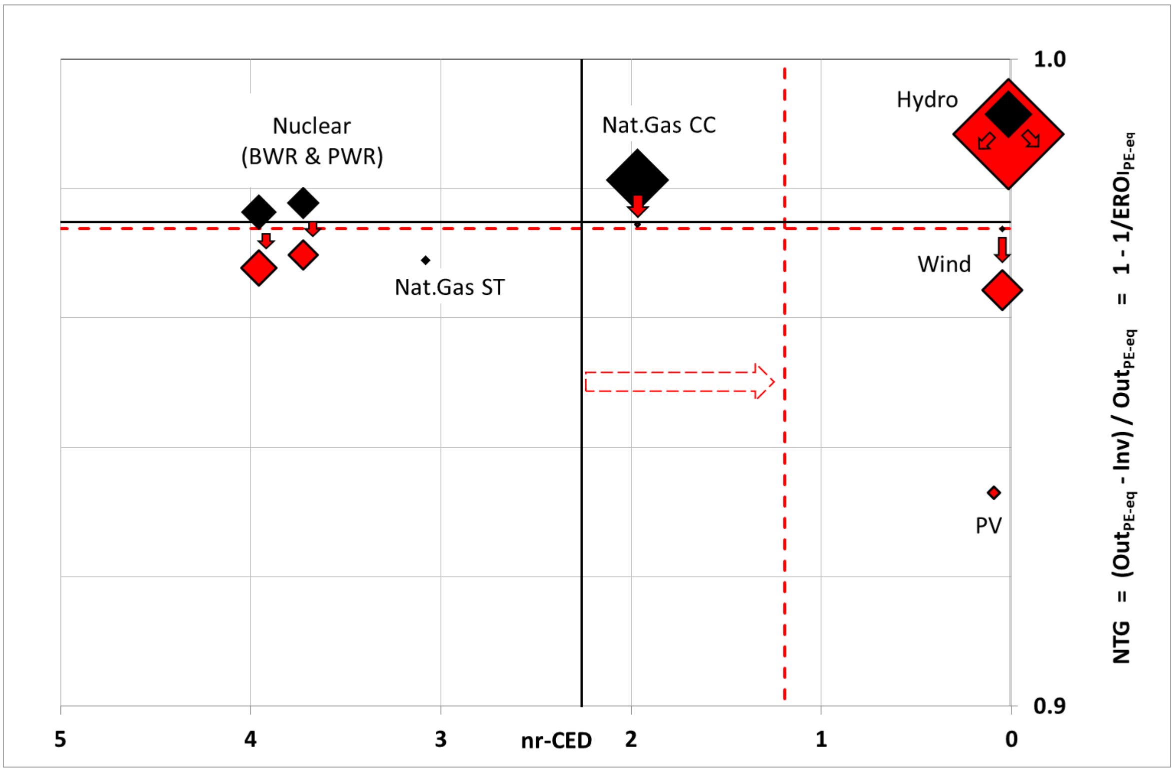


**Figure 5.** nr-CED (0-5 linear scale along horizontal axis) and NTG (0.9-1.0 linear scale along vertical axis) of electricity generators comprising the New York grid mix in 2018 (black/solid symbols) and 2030 (red/hollow symbols). Symbol sizes are proportional to gross generation by each technology. The overall nr-CED and NTG of the entire grid mixes are superimposed as continuous black lines for 2018, and dashed red lines for 2030.

But the most interesting insights are derived when carefully comparing the grid mix results for 2018 to those for 2030. It may thus be observed that the net-to-gross (NTG) ratio of the electricity produced by the New York grid as a whole is slightly diminished, from 0.975 to 0.974. This barely-registering change corresponds to a reduction in the $EROI_{PE\text{-}eq}$ of the grid from 40 to 38, which is entirely due to the *increase* in the life-cycle efficiency of the grid itself ($\eta_G$), from 0.52 to 0.70. In other words, despite the fact that in 2030 one unit of electricity in New York will only be "worth" 1/0.7 = 1.4 units of primary energy (*vs*. 1/0.52 = 1.9 units today), and notwithstanding the comparatively large deployment of PHS, the NY grid will still deliver essentially the same share of its output as net energy available for multiple societal uses, with a total "primary energy cost" of under 3% (relative to the gross electricity output expressed in terms of its primary energy equivalent). *This is a very significant result, which indicates that the 70% renewable target imposed by Bill S6599 does not entail appreciable setbacks in terms of the delivery of a net energy surplus to all the societal sectors that depend on it.*

At the same time, it is noteworthy that while the total benefits of the new renewable technologies in terms of their energy "returns" will be reaped over the course of approximately three decades (the typical lifetime of wind and PV systems), many of the associated energy investments for their deployment will have to be made up front, over a shorter time span of just over one decade. This temporal mismatch between the two timescales could, in some instances, result in a temporary "dip" in the initial year-by-year availability of net energy, as discussed elsewhere in the literature.[43] While this fact needs to be duly taken into account in terms of energy policy planning, it is our opinion that, in light of the overall positive longer-term EROI and NTG results shown here, it should not be seen as reason not to embark on this transition, but rather as a necessary adoption of the "sower's strategy" (whereby today's energy "seeds" are planted to reap the energy "crops" of tomorrow).

Finally, in terms of total demand for non-renewable primary energy, Figure 5 shows that the nr-CED of the electricity produced by the New York grid is reduced from 2.3 to 1.2, i.e., a reduction of 47.5%. *By all accounts, this is a significant improvement in terms of reduced dependence on non-renewable resources, and hence increased long-term sustainability.* Additionally, since NY state does not produce any fossil fuels or uranium, this represents a reduction in dependence on energy imports to the state, and an improvement in its energy sovereignty.

## 5. Conclusions

Our joint life-cycle greenhouse gas emission and non-renewable energy analysis has demonstrated that the ambitious renewable energy targets set by the latest legislation in New York are very effective at reducing the carbon intensity of the state's electricity mix (by as much as 92%), while at the same time they clearly improve the state's energy sovereignty (by a factor of 2). At the same time, the parallel net energy analysis – performed with consistent system boundaries and using the same inventory data – has indicated incontrovertibly that the often voiced fears that such remarkable improvements may come at the cost of significantly reduced availability of net energy for other societal uses are fundamentally unfounded.

Of course, it bears reminding that these results are only strictly valid for the specific case of New York, with all the associated assumptions in terms of technologies to be deployed (including pumped hydro storage), and they should not be casually transferred to other contexts or scenarios which may differ in some, or in some cases even all, of those important premises. But what, in our opinion, is and remains universally valid is the analytical approach described here, which rests on the long-standing traditions of Net Energy Analysis and Life Cycle Assessment, integrated in a single coherent, consistent framework.

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**Table 1.** Net electricity generation and share of total net (i.e., delivered) generation by unit type. Data from 2018 New York State Gold Book, Table III-2, Existing Generating Facilities (NYISO 2018).

| Unit Type | Abbreviation | Renewable or Fossil | Net Electricity Generation (GWh) | Share of Net Generation (%) |
|---|---|---|---|---|
| Combined Cycle (Nat. Gas) | CC | Fossil | 40,242 | 31% |
| Hydropower | HY | Renewable | 29,554 | 23% |
| Nuclear (Boiling Water Reactor) | NB | N/A | 22,215 | 17% |
| Nuclear (Pressurized Water Reactor) | NP | N/A | 19,960 | 15% |
| Steam Turbine | ST | Fossil | 11,452 | 9% |
| Wind Turbine | WT | Renewable | 4,219 | 3% |
| Combustion Turbine | GT | Fossil | 1,098 | 1% |
| Jet Engine | JE | Fossil | 864 | 1% |
| Internal Combustion | IC | Fossil | 735 | 1% |
| Photovoltaic | PV | Renewable | 47 | 0.04% |
| | | Total | 130,387 | 100% |

**Table 2.** Bounded technical potential (BTP) and economic potential for the main renewable energy resources in New York, according to estimates by NYSERDA (2014).[32]

| Renewable Technology | New Renewable Electric Installed Capacity (GW) | | | |
|---|---|---|---|---|
| | 2020 | | 2030 | |
| | BTP | Economic | BTP | Economic |
| Hydro (conventional) | 0.51 | 0.14 | 2.54 | 1.91 |
| Wind (onshore) | 2.01 | 0.44 | 4.98 | 2.17 |
| Wind (offshore) | 0.56 | 0.00 | 6.40 | 0.63 |
| Photovoltaics | 14.30 | 2.51 | 42.47 | 9.99 |

**TOC:**

**The renewable energy transition works!** New York's ambitious target to generate 70% of its electricity using renewables by 2030 is analysed by combining LCA and net energy analysis (EROI). Results prove that not only is such a target effective at slashing carbon emissions and curbing dependence on imported non-renewable feedstocks, but it also maintains existing net energy delivery.

**Keyword energy transition**

*David J. Murphy, and Marco Raugei**

**The Energy Transition in New York:**
**A Greenhouse Gas, Net Energy and Life-Cycle Energy Analysis**

**TOC figure:**