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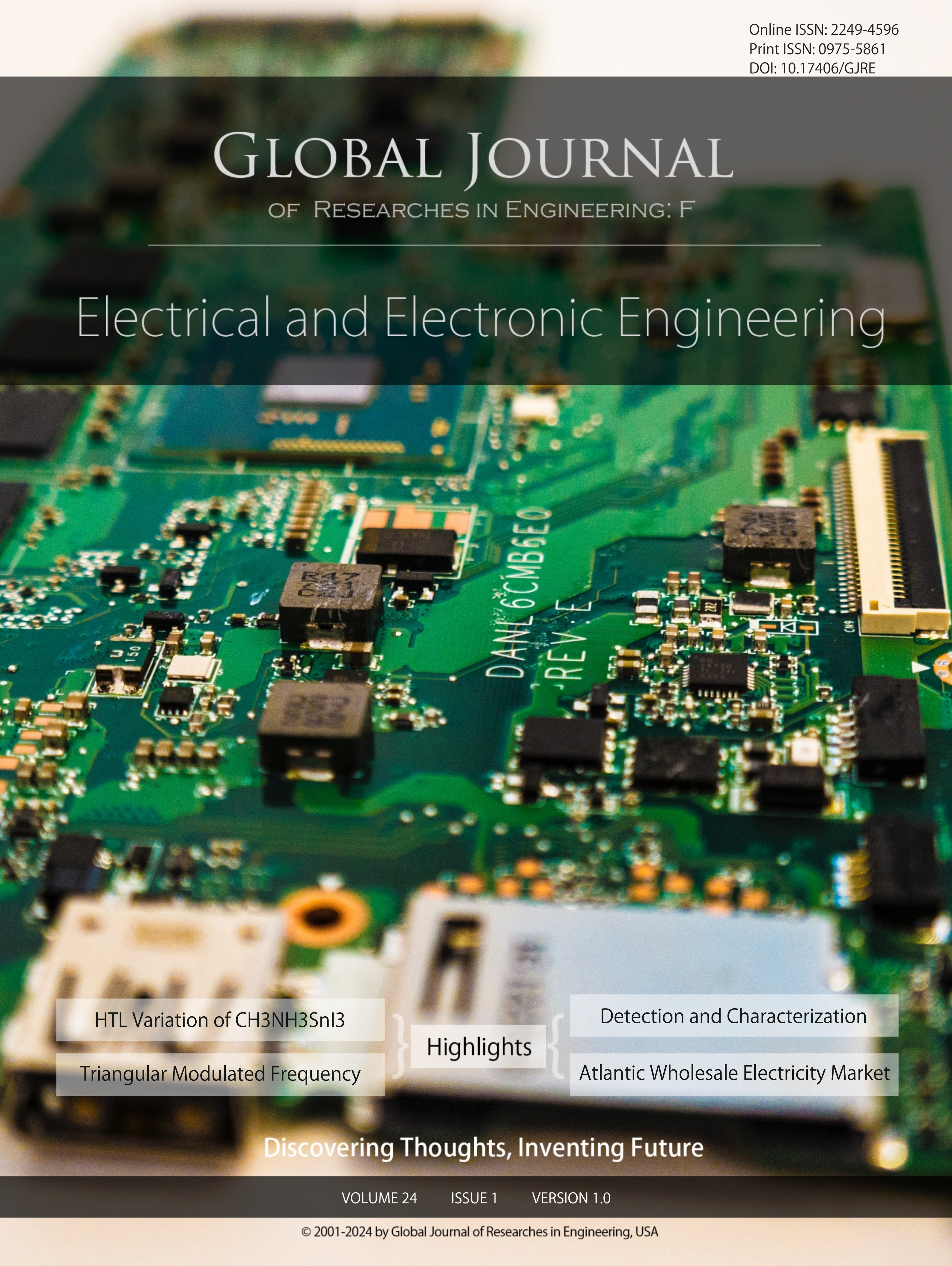

Highlights

- HTL Variation of CH3NH3SnI3
- Triangular Modulated Frequency
- Detection and Characterization
- Atlantic Wholesale Electricity Market

Discovering Thoughts, Inventing Future

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Detection and Characterization of Low Probability of Intercept Triangular Modulated Frequency Modulated Continuous Wave Radar Signals in Low SNR Environments using the Scalogram and the Reassigned Scalogram

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Daniel L. Stevens α & Solomon O. Stevens σ

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I. LPI Radar Overview

Many users of radar today are specifying Low Probability of Intercept (LPI) as an important tactical requirement [PAC09] [STO13]. The term LPI (whose meaning is not absolutely precise) [SCH06], [WIL06] is that property of a radar that, because of its low power, high duty cycle, ultra-low sidelobes, power management, wide bandwidth, frequency/phase modulation, and other design attributes, makes it difficult to be detected by means of intercept receivers such as electronic support receivers, electronic intelligence receivers, and radar warning receivers [WSQ19]. The goal of the LPI radar is to detect targets at longer ranges than the intercept receiver can detect the LPI radar. It is important to note that defining a radar to be LPI necessitates defining the corresponding intercept receiver. That is, the success of an LPI radar is measured by how hard it is for the intercept receiver to detect and intercept the radar emissions.

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One formal definition is as follows: A low probability of intercept (LPI) radar is defined as a radar that uses a special emitted waveform intended to prevent a non-cooperative intercept receiver from intercepting and detecting its emission [PAC09].

The LPI emitter has established itself as the premier tactical and strategic radar in the military spectrum. In addition to surveillance and navigation, the LPI emitter also operates in the time-critical domain for applications such as fire control and missile guidance [WIL06].

II. LPI Radar Characteristics

Some of the characteristics of the LPI radar are power management, ultra-low side lobes, and pulse compression.

Power management is the radar's ability to control the power level so that it emits only the necessary power for detection of a target. An intercept receiver is used to seeing an increase in power as the radar approaches. If a power managed LPI radar decreases the power as it approaches the target, an intercept receiver may incorrectly assume that the radar is not approaching, and therefore that no response management is necessary, which could be a deadly decision [WIL06] [SHC19].

Ultra-low side lobes prevent an intercept receiver from detecting radar emissions from the side lobes of the radar. Ultra-low side lobes are required to be -45dB or lower [SON22].

Pulse compression is another important LPI radar characteristic. For frequency modulation LPI radars, the transmitted Continuous Wave (CW) signal is coded with a reference signal that spreads the transmitted energy in frequency, making it more difficult for an intercept receiver to detect and identify the LPI radar. The reference signal can be a linear frequency modulated signal or an Frequency Shift Keying (FSK) (frequency hopping). The most popular implementation has been the Frequency Modulated Continuous Wave (FMCW) [GUL07], [LIX23].

Global Journal of Research in Engineering (F) XXIV Issue I Version I Year 2024

If the radar uses an FMCW waveform, the processing gain (apart from any noncoherent integration) is the sweep or modulation period t_m, multiplied by the sweep (input) bandwidth, ΔF (see equation (1)). That is:

$$PG_R = t_m \Delta F \qquad (1)$$

The LPI receiver compresses (correlates) the received signal from the target using the stored reference signal, for the purpose of performing target detection. The correlation receiver is a 'matched receiver' if the reference signal is exactly the same duration as the finite duration return signal [PAC09], [WIL06].

III. LPI Radar Waveforms

This section looks at the FMCW radar waveform.

FMCW is a signal that is frequently encountered in modern radar systems [VGS17]. The frequency modulation spreads the transmitted energy over a large modulation bandwidth ΔF, providing good range resolution that is critical for discriminating targets from clutter. The power spectrum of the FMCW signal is nearly rectangular over the modulation bandwidth, so non-cooperative interception is difficult. Since the transmit waveform is deterministic, the form of the return signals can be predicted. This gives it the added advantage of being resistant to interference (such as jamming), since any signal not matching this form can be suppressed [WIL06]. Consequently, it is difficult for an intercept receiver to detect the FMCW waveform and measure the parameters accurately enough to match the jammer waveform to the radar waveform [PAC09].

The most popular linear modulation utilized is the triangular modulated FMCW emitter, since it can measure the target's range and Doppler [MIL18]. Triangular modulated FMCW is the waveforms that is employed in this paper.

IV. Detection of LPI Radars: Intercept Receiver Overview

In this section we switch from the topic of LPI radars, to the topic of those devices that detect and characterize LPI radar signals – intercept receivers.

The three main types of intercept receivers are: electronic support receivers, electronic intelligence receivers, and radar warning receivers.

Electronic intelligence is the result of observing the signals transmitted by radar systems to obtain information about their capabilities: it is the remote sensing of remote sensors. Through electronic intelligence, it is possible to obtain valuable information while remaining remote from the radar itself. Identification is performed by comparing the intercepted signal signature against the signatures contained within its threat library [CLA13]. Clearly, the underlying basic function of electronic intelligence is to determine the capabilities of the radar, so that decisions can be made as to what threat it poses [GRA11]. Electronic intelligence receivers are the least time critical of the three intercept receivers. The outputs of the electronic intelligence receiver may be analyzed using off-line analysis tools based on software.

Radar warning receivers are designed to give nearly immediate warning if specific threat signals are received (e.g., illumination of an aircraft's warning receiver by the target tracking radar of a threatening system). The warning receiver typically has poor sensitivity and feeds into a near-real-time processor that uses a few parameter measurements to identify a threat. Usually, rough direction (e.g., quadrant or octant) is determined for the threat and the operator has a crude display showing functional radar type, direction, and relative range (strong signals displayed as being nearer than weaker ones). This type of receiver does not provide the kind of output that is analyzed using the methods described later in this paper.

Electronic support receivers encompass all actions necessary to provide the information required for immediate decisions involving electronic warfare operations, threat avoidance, targeting, and homing [ASC16], [WIL06].

V. Intercept Receiver Signal Analysis Techniques

This section describes some of the classical time-frequency analysis techniques as well as the reassignment method utilized in this paper.

a) *Time-Frequency Analysis*

Time-frequency signal analysis concerns the analysis and processing of signals with time-varying frequency content. Such signals are best represented by a time-frequency distribution, which is intended to show how the energy of the signal is distributed over the two-dimensional time-frequency plane [ZML16]. Processing of the signal may then exploit the features produced by the concentration of signal energy in two dimensions (time and frequency), instead of only one dimension (time or frequency) [BOA15]. Since noise tends to spread out evenly over the time-frequency domain, while signals concentrate their energies within limited time intervals and frequency bands; the local SNR of a noisy signal can be improved simply by using time-frequency analysis [BOA15]. Also, the intercept receiver can increase its processing gain by implementing time-frequency signal analysis [GHA20].

As alluded to previously, time-frequency distributions are useful for the visual interpretation of signal dynamics, as an experienced operator can quickly detect a signal and extract the signal parameters by analyzing the time-frequency distribution [BOA15].

b) Scalogram (Wavelet Transform)

The wavelet transform will be examined first, and then connected to the Scalogram. The Scalogram is defined as the magnitude squared of the wavelet transform, and can be used as a time-frequency distribution [BOA15], [SIA21].

The idea of the wavelet transform (equation (2)) is to project a signal x on a family of zero-mean functions (the wavelets) deduced from an elementary function (the mother wavelet) by translations and dilations:

$$T_x(t,a;\Psi) = \int_{-\infty}^{+\infty} x(s)\Psi_{t,a}^{*}(s)ds \tag{2}$$

where $\Psi_{t,a}(s) = |a|^{-1/2}\Psi\left(\frac{s-t}{a}\right)$. The variable a corresponds to a scale factor, in the sense that taking $|a| > 1$ dilates the wavelet Ψ and taking $|a| < 1$ compresses Ψ. By definition, the wavelet transform is more a time-scale than a time-frequency representation. However, for wavelets which are well localized around a non-zero frequency ν_0 at a scale $= 1$, a time-frequency interpretation is possible thanks to the formal identification $\nu = \frac{\nu_0}{a}$.

The wavelet transform is of interest for the analysis of non-stationary signals, because it provides still another alternative to the Short-Time Fourier transform (STFT) and to many of the quadratic time-frequency distributions. The basic difference between the STFT and the wavelet transform is that the STFT uses a fixed signal analysis window, whereas the wavelet transform uses short windows at high frequencies and long windows at low frequencies. This helps to diffuse the effect of the uncertainty principle by providing good time resolution at high frequencies and good frequency resolution at low frequencies. This approach makes sense especially when the signal at hand has high frequency components for short durations and low frequency components for long durations. The signals encountered in practical applications are often of this type.

The wavelet transform allows localization in both the time domain via translation of the mother wavelet, and in the scale (frequency) domain via dilations. The wavelet is irregular in shape and compactly supported, thus making it an ideal tool for analyzing signals of a transient nature; the irregularity of the wavelet basis lends itself to analysis of signals with discontinuities or sharp changes, while the compactly supported nature of wavelets enables temporal localization of a signal's features [HEZ16]. Unlike many of the quadratic functions such as the Wigner-Ville Distribution (WVD) and Choi-Williams Distribution (CWD), the wavelet transform is a linear transformation, therefore cross-term interference is not generated. There is another major difference between the STFT and the wavelet transform; the STFT uses sines and cosines as an orthogonal basis set to which the signal of interest is effectively correlated against, whereas the wavelet transform uses special 'wavelets' which usually comprise an orthogonal basis set. The wavelet transform then computes coefficients, which represents a measure of the similarities, or correlation, of the signal with respect to the set of wavelets. In other words, the wavelet transform of a signal corresponds to its decomposition with respect to a family of functions obtained by dilations (or contractions) and translations (moving window) of an analyzing wavelet.

A filter bank concept is often used to describe the wavelet transform. The wavelet transform can be interpreted as the result of filtering the signal with a set of bandpass filters, each with a different center frequency [PRL19].

Like the design of conventional digital filters, the design of a wavelet filter can be accomplished by using a number of methods including weighted least squares [WAL13], orthogonal matrix methods [ANS10], nonlinear optimization, optimization of a single parameter (e.g. the passband edge) [GUT22] and a method that minimizes an objective function that bounds the out-of-tile energy [STS16].

Here are some properties of the wavelet transform: 1) The wavelet transform is covariant by translation in time and scaling. The corresponding group of transforms is called the Affine group; 2) The signal x can be recovered from its wavelet transform via the synthesis wavelet; 3) Time and frequency resolutions, like in the STFT case, are related via the Heisenberg-Gabor inequality. However in the wavelet transform case, these two resolutions depend on the frequency: the frequency resolution becomes poorer and the time resolution becomes better as the analysis frequency grows; 4) Because the wavelet transform is a linear transform, it does not contain cross-term interferences [SKZ21].

Since the wavelet transform behaves like an orthonormal basis decomposition, it can be shown that it preserves energy:

$$\iint_{-\infty}^{+\infty} |T_x(t,a;\Psi)|^2 \; dt\frac{da}{a^2} = E_x \tag{3}$$

where E_x is the energy of x . This leads us to define the Scalogram (equation (3)) of x as the squared modulus of the wavelet transform. It is an energy distribution of the signal in the time-scale plane, associated with the measure $\frac{da}{a^2}$.

As is the case for the wavelet transform, the time and frequency resolutions of the Scalogram are related via the Heisenberg-Gabor principle.

The interference terms of the Scalogram, as for the Spectrogram (the squared modulus of the STFT), are also restricted to those regions of the time-frequency plane where the corresponding signals overlap. Therefore, if two signal components are sufficiently far apart in the time-frequency plane, their cross-Scalogram will be essentially zero [STS17].

For this paper, the Morlet Scalogram will be used. The Morlet wavelet is obtained by taking a complex sine wave and localizing it with a Gaussian envelope. The Mexican hat wavelet isolates a single bump of the Morlet wavelet. The Morlet wavelet has good focusing in both time and frequency [YCC14].

c) The Reassignment Method

Bilinear time-frequency distributions offer a wide range of methods designed for the analysis of non stationary signals. Nevertheless, a critical point of these methods is their readability [ZHF22], which means both a good concentration of the signal components along with few misleading interference terms. A lack of readability, which is a known deficiency in the classical time-frequency analysis techniques, must be overcome in order to obtain time-frequency distributions that can be both easily read by non-experts and easily included in a signal processing application [BOA15]. Inability to obtain readable time-frequency distributions may lead to inaccurate signal metrics extraction, which in turn can bring about an uninformed and therefore potentially unsafe intercept receiver environment.

Some efforts have been made in that direction, and in particular, a general methodology referred to as reassignment.

The original idea of reassignment was introduced in an attempt to improve the Spectrogram [MIJ18]. As with any other bilinear energy distribution, the Spectrogram is faced with an unavoidable trade-off between the reduction of misleading interference terms and a sharp localization of the signal components.

We can define the Spectrogram as a two-dimensional convolution of the WVD of the signal by the WVD of the analysis window, as in equation (4):

$$S_x(t,f;h) = \iint_{-\infty}^{+\infty} W_x(s,\xi)W_h(t-s,f-\xi)ds\,d\xi \quad (4)$$

Therefore, the distribution reduces the interference terms of the signal's WVD, but at the expense of time and frequency localization. However, a closer look at equation 4 shows that $W_h(t-s,f-\xi)$ delimits a time-frequency domain at the vicinity of the (t,f) point, inside which a weighted average of the signal's WVD values is performed. The key point of the reassignment principle is that these values have no reason to be symmetrically distributed around (t,f), which is the geometrical center of this domain. Therefore, their average should not be assigned at this point, but rather at the center of gravity of this domain, which is much more representative of the local energy distribution of the signal. Reasoning with a mechanical analogy, the local energy distribution $W_h(t-s,f-\xi)W_x(s,\xi)$ (as a function of s and ξ) can be considered as a mass distribution, and it is much more accurate to assign the total mass (i.e. the Spectrogram value) to the center of gravity of the domain rather than to its geometrical center. Another way to look at it is this: the total mass of an object is assigned to its geometrical center, an arbitrary point which except in the very specific case of a homogeneous distribution, has no reason to suit the actual distribution. A much more meaningful choice is to assign the total mass of an object, as well as the Spectrogram value, to the center of gravity of their respective distribution [BOA15], [FAC18].

This is exactly how the reassignment method proceeds: it moves each value of the Spectrogram computed at any point (t,f) to another point $(\hat{t},\hat{f})$ which is the center of gravity of the signal energy distribution around (t,f) (see equations (5) and (6)) [MIB16]:

$$\hat{t}(x;t,f) = \frac{\iint_{-\infty}^{+\infty} s\, W_h(t-s,f-\xi)W_x(s,\xi)ds\,d\xi}{\iint_{-\infty}^{+\infty} W_h(t-s,f-\xi)W_x(s,\xi)ds\,d\xi} \quad (5)$$

$$\hat{f}(x;t,f) = \frac{\iint_{-\infty}^{+\infty} \xi\, W_h(t-s,f-\xi)W_x(s,\xi)ds\,d\xi}{\iint_{-\infty}^{+\infty} W_h(t-s,f-\xi)W_x(s,\xi)ds\,d\xi} \quad (6)$$

and thus leads to a reassigned Spectrogram (equation (7)), whose value at any point (t',f') is the sum of all the Spectrogram values reassigned to this point:

$$S_x^{(r)}(t',f';h) = \iint_{-\infty}^{+\infty} S_x(t,f;h)\delta\left(t'-\hat{t}(x;t,f)\right)\delta\left(f'-\hat{f}(x;t,f)\right)dt\,df \quad (7)$$

Global Journal of Research in Engineering (F) XXIV Issue I Version I Year 2024

One of the most interesting properties of this new distribution is that it also uses the phase information of the STFT, and not only its squared modulus as in the Spectrogram. It uses this information from the phase spectrum to sharpen the amplitude estimates in time and frequency. This can be seen from the following expressions of the reassignment operators:

$$\hat{t}(x;t,f) = -\frac{d\Phi_x(t,f;h)}{df} \quad (8)$$

$$\hat{f}(x;t,f) = f + \frac{d\Phi_x(t,f;h)}{dt} \quad (9)$$

where $\Phi_x(t,f;h)$ is the phase of the STFT of x : $\Phi_x(t,f;h) = \arg(F_x$ (t, f; h)). However, these expressions (equations (8) and (9)) do not lead to an efficient implementation, and have to be replaced by equations(10) (local group delay) and (11) (local instantaneous frequency):

$$\hat{t}(x;t,f) = t - \Re\left\{\frac{F_x(t,f;T_{h)}F_x^*(t,f;h)}{\left|F_{x(t,f;h)}\right|^2}\right\} \quad (10)$$

$$\hat{f}(x;t,f) = f - \Im\left\{\frac{F_x(t,f;D_{h)}F_x^*(t,f;h)}{\left|F_{x(t,f;h)}\right|^2}\right\} \quad (11)$$

where $T_h(t) = t \times h(t)$ and $D_h(t) = \frac{dh}{dt}(t)$. This leads to an efficient implementation for the Reassigned Spectrogram without explicitly computing the partial derivatives of phase. The Reassigned Spectrogram may thus be computed by using 3 STFTs, each having a different window (the window function h; the same window with a weighted time ramp t*h; the derivative of the window function h with respect to time (dh/dt)). Reassigned Spectrograms are therefore very easy to implement, and do not require a drastic increase in computational complexity.

The reassignment principle for the Spectrogram allows for a straight-forward extension of its use to other distributions as well [BOA15], [FAC18]. If we consider the general expression of a distribution of the Cohen's class as a two-dimensional convolution of the WVD, as in equation 12:

$$C_x(t,f;\Pi) = \iint_{-\infty}^{+\infty} \Pi(t-s,f-\xi)W_x(s,\xi)ds\,d\xi \quad (12)$$

replacing the particular smoothing kernel $W_h(u,\xi)$ by an arbitrary kernel $\Pi(s,\xi)$ simply defines the reassignment of any member of Cohen's class (equations 13 through 15):

$$\hat{t}(x;t,f) = \frac{\iint_{-\infty}^{+\infty} s\,\Pi(t-s,f-\xi)W_x(s,\xi)ds\,d\xi}{\iint_{-\infty}^{+\infty} \Pi(t-s,f-\xi)W_x(s,\xi)ds\,d\xi} \quad (13)$$

$$\hat{f}(x;t,f) = \frac{\iint_{-\infty}^{+\infty} \xi\,\Pi(t-s,f-\xi)W_x(s,\xi)ds\,d\xi}{\iint_{-\infty}^{+\infty} \Pi(t-s,f-\xi)W_x(s,\xi)ds\,d\xi} \quad (14)$$

$$C_x^{(r)}(t',f';\Pi) = \iint_{-\infty}^{+\infty} C_x(t,f;\Pi)\delta\left(t'-\hat{t}(x;t,f)\right)\delta\left(f'-\hat{f}(x;t,f)\right)dt\,df \quad (15)$$

The resulting reassigned distributions efficiently combine a reduction of the interference terms provided by a well adapted smoothing kernel and an increased concentration of the signal components achieved by the reassignment. In addition, the reassignment operators $\hat{t}(x;t,f)$ and $\hat{f}(x;t,f)$ are almost as easy to compute as for the Spectrogram [YUG19].

Similarly, the reassignment method can also be applied to the time-scale energy distributions [BOA15], [FAC18]. Starting from the general expression in equation (16):

$$\Omega_x(t,a;\Pi) = \iint_{-\infty}^{+\infty} \Pi(s/a, f_0 - a\xi)W_x(t-s,\xi)\,ds\,d\xi \quad (16)$$

we can see that the representation value at any point $(t, a = f_0/f)$ is the average of the weighted WVD values on the points $(t-s,\xi)$ located in a domain centered on (t,f) and bounded by the essential support of Π. In order to avoid the resultant signal components broadening while preserving the cross-terms attenuation, it seems once again appropriate to assign this average to the center of gravity of these energy measures, whose coordinates are shown in equations (17) and (18):

$$\hat{t}(x;t,f) = t - \frac{\iint_{-\infty}^{+\infty} s\,\Pi(s/a\,,f_0 - a\xi)W_x(t-s,\xi)ds\,d\xi}{\iint_{-\infty}^{+\infty} \Pi(s/a\,,f_0 - a\xi)W_x(t-s,\xi)ds\,d\xi} \quad (17)$$

$$\hat{f}(x;t,f) = \frac{f_0}{\hat{a}(x;t,f)} = \frac{\iint_{-\infty}^{+\infty} \xi\,\Pi(s/a\,,f_0 - a\xi)W_x(t-s,\xi)ds\,d\xi}{\iint_{-\infty}^{+\infty} \Pi(s/a\,,f_0 - a\xi)W_x(t-s,\xi)ds\,d\xi} \quad (18)$$

rather than to the point $(t, a = f_0/f)$ where it is computed. The value of the resulting modified time-scale representation on any point $(t^{'}, a^{'})$ is then the sum of all the representation values moved to this point, and is known as the reassigned Scalogram (equation (19)):

$$\Omega_x^{(r)}(t^{'},a^{'};\Pi) = \iint_{-\infty}^{+\infty} a^{'2}\,\Omega_x(t,a;\Pi)\delta\big(t^{'} - \hat{t}(x;t,a)\big)\delta\big(a^{'} - \hat{a}(x;t,a)\big)dt\frac{da}{a^2} \quad (19)$$

As for Cohen's class, it can be shown that these modified distributions are also theoretically perfectly localized for chirps and impulses.

It can be noted that the smoothing and squeezing qualities of the reassignment method lead to improved readability, which in turn, leads to more accurate metrics extraction, which may create a more informed and safer intercept receiver environment.

The reassignment method utilized in this paper is the Reassigned Scalogram.

VI. Methodology

The methodologies detailed in this section describe the processes involved in obtaining and comparing metrics between utilization of the Scalogram and the Reassigned Scalogram time-frequency analysis techniques for the detection and characterization of low probability of intercept triangular modulated FMCW radar signals.

The tools used for this testing were: Matrix Laboratory (MATLAB) (version 8.3), Signal Processing Toolbox (version 6.21), Wavelet Toolbox (version 4.7), Image Processing Toolbox (version 7.2), and Time-Frequency Toolbox (version 1.0) (http://tftb.nongnu .org/).

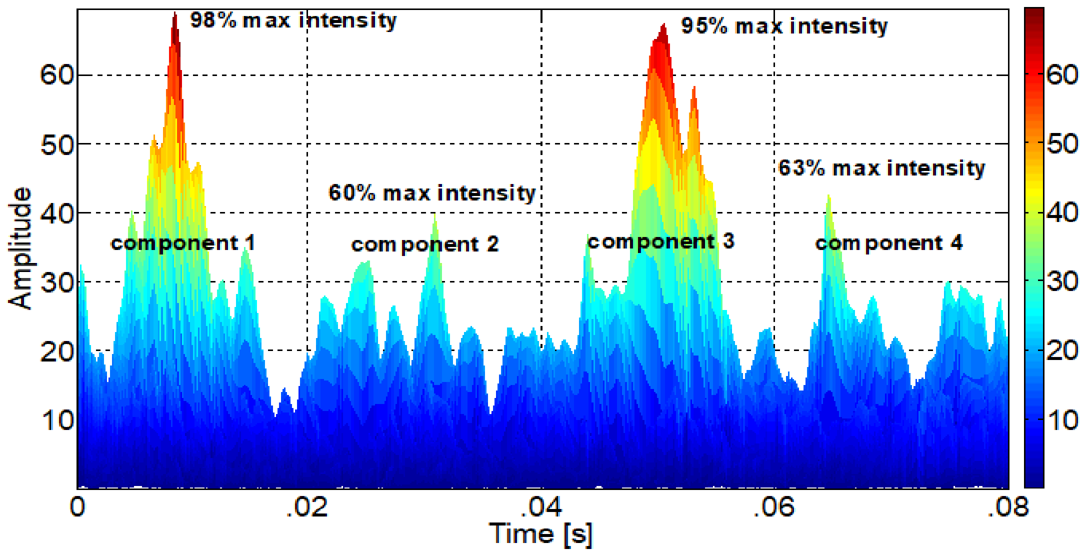
All testing was accomplished on a desktop computer (Dell Precision T1700; Processor - Intel Xeon CPU E3-1226 v3 3.30GHz; Installed RAM - 32.0GB; System type - 64-bit operating system, x64-based processor).

Testing was performed for a triangular modulated FMCW waveform (parameters: sampling frequency=6KHz; carrier frequency=1.5KHz; modulation bandwidth=2400Hz; modulation period=.015sec). The waveform parameters were chosen for academic validation of signal processing techniques. Due to computer processing resources they were not meant to represent real-world values. The number of samples for each test was chosen to be 512, which seemed to be the optimum size for the desktop computer. Testing was performed at three different Signal-to-Noise (SNR) levels: 10dB, 0dB, and the lowest SNR at which the signal could be detected. The noise added was white Gaussian noise, which best reflects the thermal noise present in the IF section of an intercept receiver [PAC09]. Kaiser windowing was used, when windowing was applicable. 100 runs were performed for each test, for statistical purposes. The time-frequency analysis techniques used for each task were the Scalogram and the Reassigned Scalogram.

After each particular run of each test, metrics were extracted from the time-frequency representation. The different metrics extracted were as follows:

1) *Percent detection:* Percent of time signal was detected - signal was declared a detection if any portion of each of the signal components (4 chirp components for triangular modulated FMCW) exceeded a set detection threshold (a certain percentage of the maximum intensity of the time-frequency representation).

Detection threshold percentages were determined based on visual detections of low SNR signals (lowest SNR at which the signal could be visually detected in the time-frequency representation) (see Figure 1).



(Note – using this methodology, the detection threshold percentages were determined to be 50% for the Scalogram, and 50% for the Reassigned Scalogram. These values were automatically set for the plots in Figure 9 of the Results Section in this paper).

Figure 1: Example plot for detection threshold percentage determination. This plot is an amplitude vs. time (x-z view) of a time-frequency analysis technique of a triangular modulated FMCW signal (SNR= -3dB). For visually detected low SNR plots (like this one), the percent of max intensity for the peak z-value of each of the signal components (the 2 legs for each of the 2 triangles of the triangular modulated FMCW) was noted (here 98%, 60%, 95%, 63%), and the lowest of these 4 values was recorded (here 60%). This process was then repeated 25 times, and the average of the lowest values was calculated, and assigned as the detection threshold percentage for this time-frequency analysis technique

For percent detection determination, these detection threshold values were included in the time-frequency plot algorithms so that the detection thresholds could be applied automatically during the plotting process. From the percent detection plot, the signal was declared a detection if any portion of each of the signal components was visible (see Figure 2).

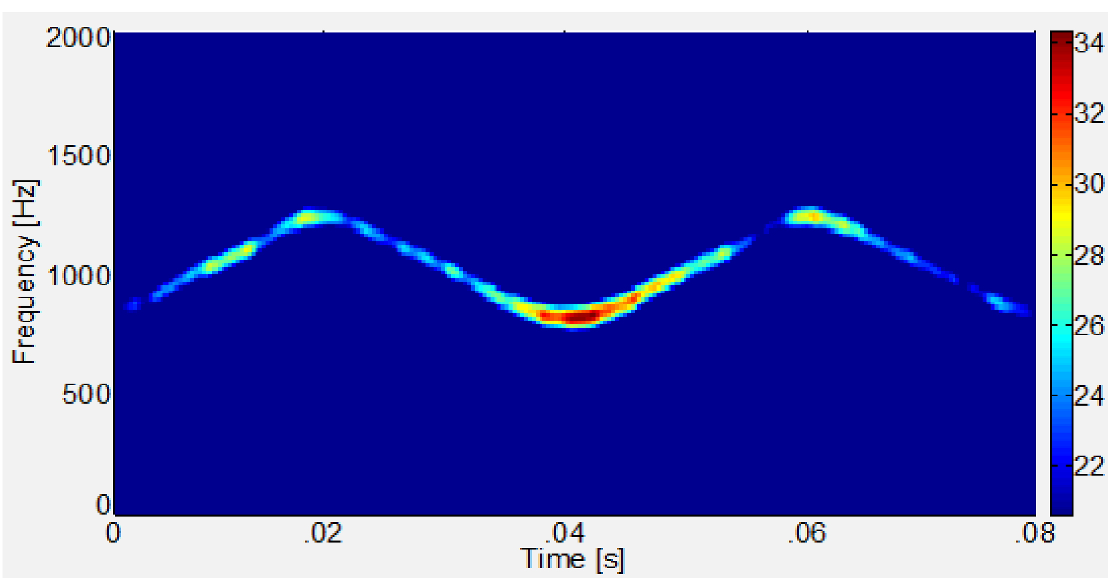


Figure 2: Example plot for determination of percent detection (time-frequency). This plot is a frequency vs. time (x-y view) of a time-frequency analysis technique of a triangular modulated FMCW signal (SNR= 10dB) with detection threshold value automatically set to 60%. From this plot, the signal was declared a (visual) detection because at least a portion of each of the 4 signal components (the 2 legs for each of the 2 triangles of the triangular modulated FMCW) was visible

2) *Lowest detectable SNR:* The lowest SNR level at which at least a portion of each of the signal components exceeded the set detection threshold listed in the percent detection section above.

For lowest detectable SNR determination, the detection threshold value was included in the time-frequency plot algorithms so that the detection threshold could be applied automatically during the plotting process. From the lowest detectable SNR plot, the signal was declared a detection if any portion of each of the signal components was visible. The lowest SNR level for which the signal was declared a detection is the lowest detectable SNR (see Figure 3).

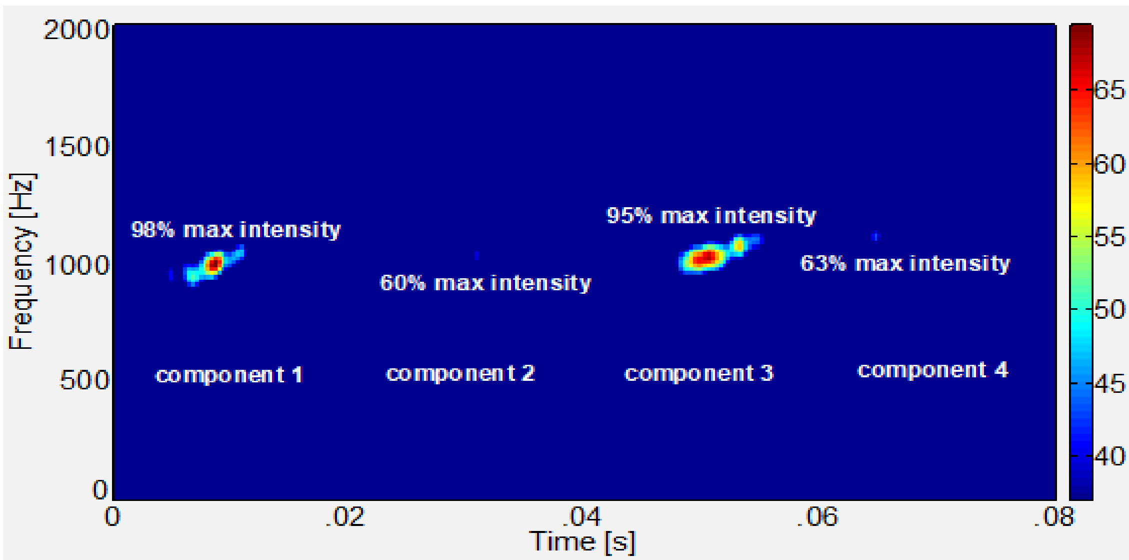


Figure 3: Example plot for determining lowest detectable SNR. This plot is an frequency vs. time (x-y view) of a time-frequency analysis technique of a triangular modulated FMCW signal (SNR= -3dB) with detection threshold value automatically set to 60%. From this plot, the signal was declared a (visual) detection because at least a portion of each of the 4 signal components (the 2 legs for each of the 2 triangles of the triangular modulated FMCW) was visible. Note that the signal portion for the 60% max intensity (just above the 'x' in 'max') is barely visible, because the detection threshold for the time-frequency analysis technique is 60%. For this case, any lower SNR would have been a non-detect. Compare to Figure 2, which is the same plot, except that it has an SNR level equal to 10dB

3) *Carrier frequency:* The frequency corresponding to the maximum intensity of the time-frequency representation (see Figure 4).

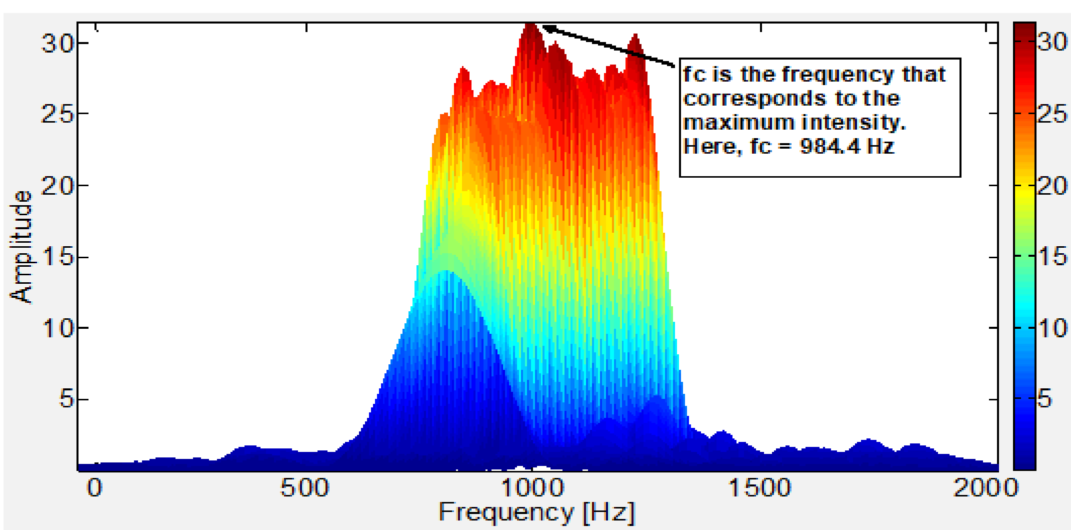


Figure 4: Example plot for determination of carrier frequency. Time-frequency analysis technique of a triangular modulated FMCW signal (SNR=10dB). From the frequency-intensity (y-z) view, the maximum intensity value is manually determined. The frequency corresponding to the max intensity value is the carrier frequency (here fc=984.4 Hz)

4) *Modulation bandwidth (modBW):* Distance from highest frequency value of signal (at a manual measurement threshold of 20% maximum intensity) to lowest frequency value of signal (at same threshold) in Y-direction (frequency).

The manual measurement threshold of 20% maximum intensity was determined based on manual measurement of the modulation bandwidth of the signal in the time-frequency representation. This was accomplished for 25 test runs for each time-frequency analysis technique, for each waveform. During each manual measurement, the max intensity of the high and low measuring points was recorded. The average of the max intensity values for these test runs, for each of the time-frequency analysis techniques, for each waveform, was 20%. This was adopted as the manual measurement threshold value, and is representative of what is obtained when performing manual measurements. This manual measurment threshold of 20% maximum intensity was also adapted for determining the modulation period and the time-frequency localization (both are described below).

For modulation bandwidth determination, the manual measurement threshold of 20% maximum intensity was included in the time-frequency plot algorithms so that the threshold could be applied automatically during the plotting process. From the modulation bandwidth plot, the modulation bandwidth was manually measured (see Figure 5).

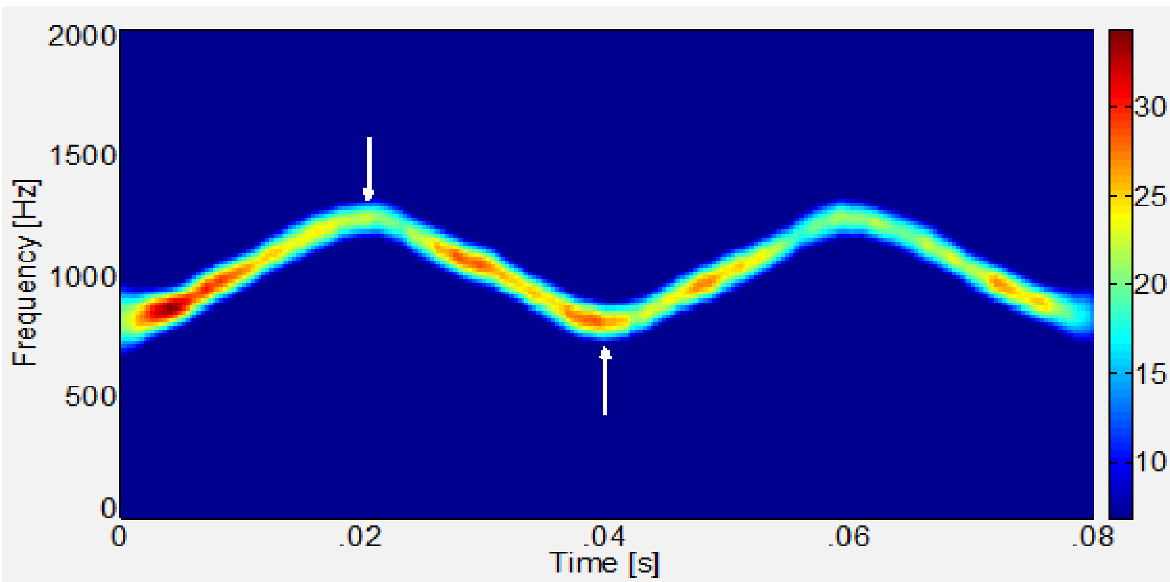


Figure 5: Example plot for modulation bandwidth determination. This plot is a time vs. frequency (x-y view) of a time-frequency analysis technique of a triangular modulated FMCW signal (SNR=10dB) with the manual measurement threshold of 20% maximum intensity automatically set. From this modulation bandwidth plot, the modulation bandwidth was measured manually from the highest frequency value of the signal (top white arrow) to the lowest frequency value of the signal (bottom white arrow) in the y-direction (frequency)

5) *Modulation period (modPer):* Distance from highest frequency value of signal (at a manual measurement threshold of 20% maximum intensity) to lowest frequency value of signal (at same threshold) in X-direction (time).

For modulation period determination, the manual measurement threshold of 20% maximum intensity was included in the time-frequency plot algorithms so that the threshold could be applied automatically during the plotting process. From the modulation period plot, the modulation bandwidth was manually measured (see Figure 6).

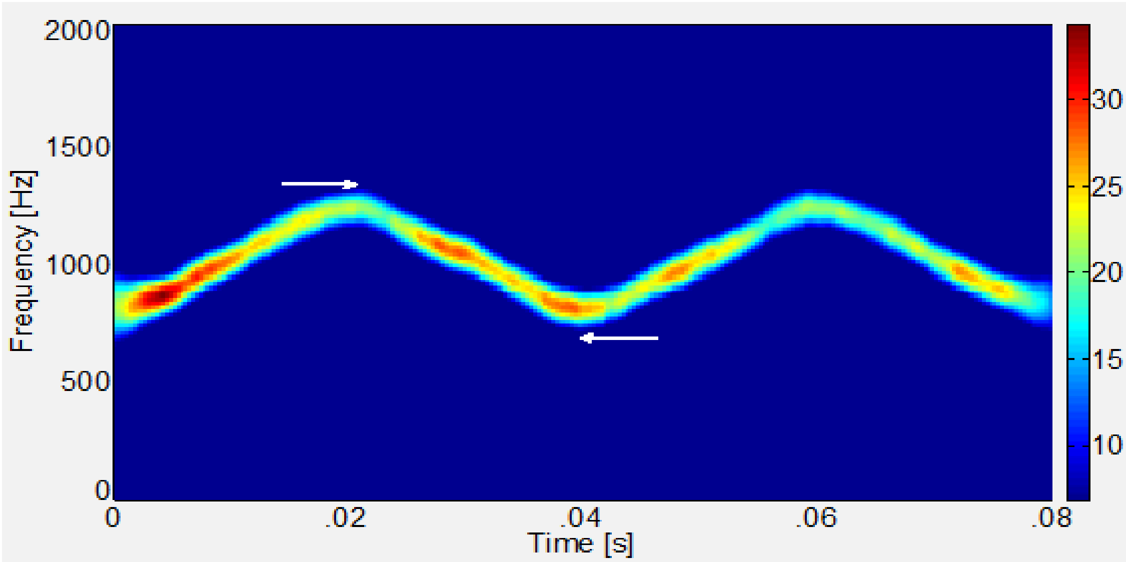


Figure 6: Example plot for modulation period determination. This plot is a time vs. frequency (x-y view) of a time-frequency analysis technique of a triangular modulated FMCW signal (SNR=10dB), with the manual measurement threshold of 20% maximum intensity automatically set. From this modulation period plot, the modulation period was measured manually from the highest frequency value of the signal (top white arrow) to the lowest frequency value of the signal (bottom white arrow) in the x-direction (time)

6) *Time-frequency localization:* Measure of the thickness of a signal component (at the manual measurement threshold of 20% maximum intensity) on each side of the component) – converted to % of entire X-Axis, and % of entire Y-Axis.

For time-frequency localization determination, the manual measurement threshold of 20% maximum intensity was included in the time-frequency plot algorithms so that the threshold could be applied automatically during the plotting process. From the time-frequency localization plot, the time-frequency localization was manually measured (see Figure 7).

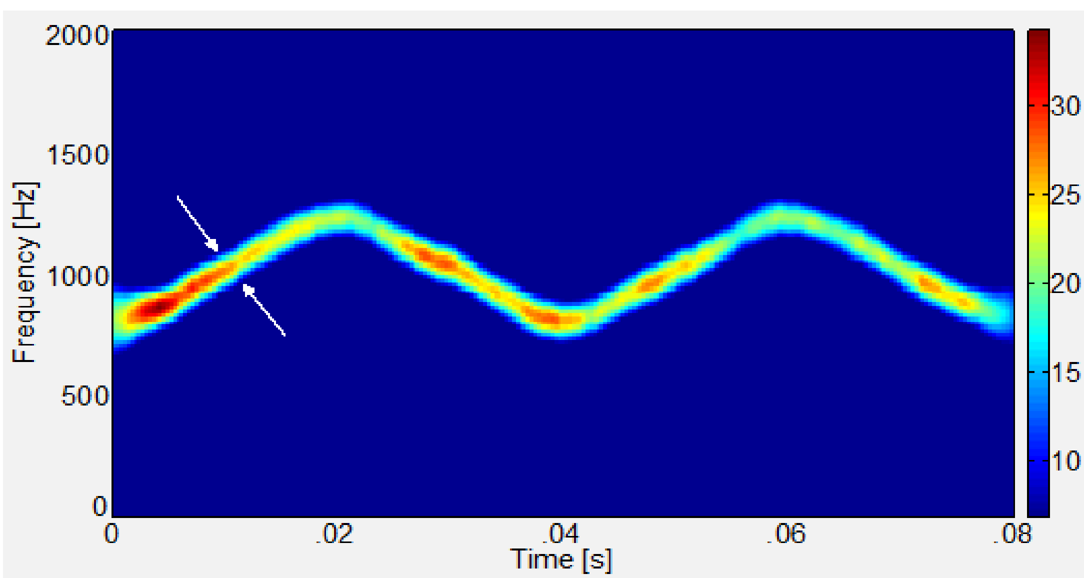


Figure 7: Example plot for time-frequency localization determination. Time-frequency analysis technique of a triangular modulated FMCW signal (SNR=10dB) with the manual measurement threshold of 20% maximum intensity automatically set. From this time-frequency localization plot, the time-frequency localization was measured manually from the left side of the signal (left white arrow) to the right side of the signal (right white arrow) in both the x-direction (time) and the y-direction (frequency). Measurements were made at the center of each of the 4 'legs', and the average values were determined. Average time and frequency 'thickness' values were then converted to: % of entire x-axis and % of entire y-axis

7) *Chirp rate: (modulation bandwidth)/(modulation period)*

The data from all 100 runs for each test was used to produce the actual, error, and percent error for each of these metrics listed above.

The metrics from the Scalogram were then compared to the metrics from the Reassigned Scalogram. By and large, the Reassigned Scalogram outperformed the Scalogram, as will be shown in the results section.

VII. Results

Table 1 presents the overall testmetrics for the two time-frequency analysis techniques used in this testing (Scalogram versus Reassigned Scalogram).

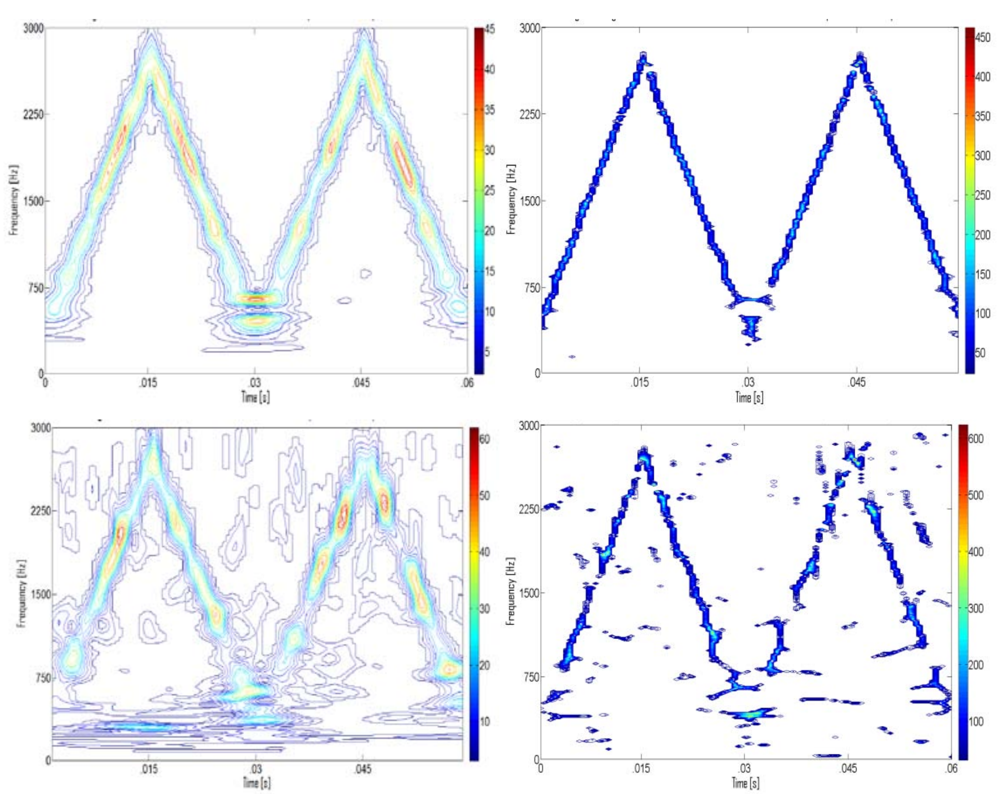
Table 1: Overall test metrics (average percent error: carrier frequency, modulation bandwidth, modulation period, chirp rate; average: percent detection, lowest detectable snr, plot time, time-frequency localization (as a percent of x axis and y axis) for the two time-frequency analysis techniques (Scalogram versus Reassigned Scalogram)

Parameters	Scalogram	Reassigned Scalogram
Carrier Frequency	9.09%	3.45%
Modulation Bandwidth	9.31%	2.88%
Modulation Period	0.61%	0.52%
Chirp Rate	9.57%	5.71%
Percent Detection	65.30%	72.10%
Lowest Detectable snr	-2.56db	-3.07db
Time-Frequency Localization-X	3.83%	2.14%
Time-Frequency Localization-Y	3.46%	1.28%

From Table 1, the Reassigned Scalogram outperformed the Scalogram in every metrics category.

Note– using this methodology, the detection threshold percentages were determined to be 50% for the Scalogram, and 50% for the Reassigned Scalogram.

Figure 9 shows comparative plots of the Scalogram (left) vs. the Reassigned Scalogram (right) (triangular modulated FMCW signal) at SNRs of 10dB (top), 0dB (middle), and -3dB (bottom).



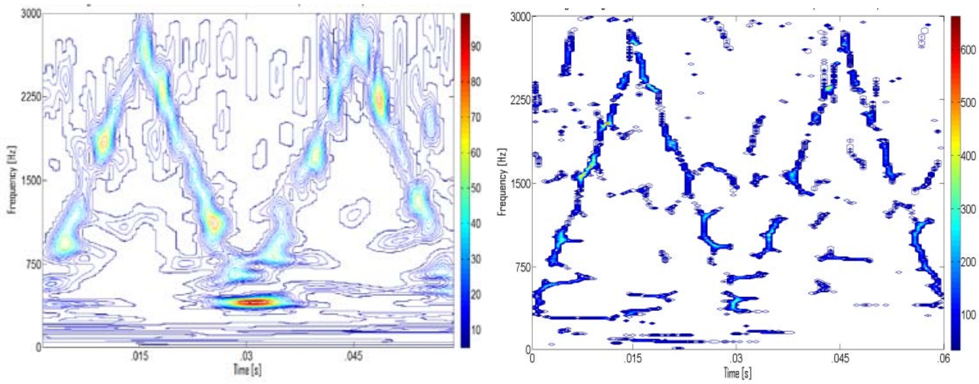


Figure 9: Comparative plots of the triangular modulated FMCW (task 2) low probability of intercept radar signals (Scalogram (left-hand side) vs. the Reassigned Scalogram (right-hand side)). The SNR for the top row is 10dB, for the middle row is 0dB, and for the bottom row is -3dB. In general, the Reassigned Scalogram signals appear more localized ('thinner') than do the Scalogram signals. In addition, the Reassigned Scalogram signals appear more readable than the Scalogram signals at every SNR level

VIII. Discussion

This section will elaborate on the results from the previous section.

From Table 1, the Reassigned Scalogram outperformed the Scalogram in every category. For the Scalogram, the poorer signal localization ('thicker' signal), when compared with the Reassigned Scalogram's 'squeezing' quality (see Figure 9), can account for the Scalogram being outperformed by the Reassigned Scalogram in the areas of: average percent error of modulation bandwidth, modulation period, chirp rate (=modBW/modPer)), time-frequency localization (x and y-direction), lowest detectable SNR, carrier frequency, and percent detection. Note that average percent detection and lowest detectable SNR are both based on visual detections in the time-frequency representation. Figure 9 shows that the signals in the Reassigned Scalogram plots are more readable than those in the Scalogram plots, which accounts for the Reassigned Scalogram's better average percent detection and lowest detectable SNR. The Scalogram might be used in a scenario with a 'quick and dirty' check to see if a signal is present, without accurate extraction of its parameters. The Reassigned Scalogram might be used in a scenario where you need accurate parameters, in a low SNR environment, in a quick time frame.

IX. Conclusions

Digital intercept receivers, whose main job is to detect and extract parameters from low probability of intercept radar signals, are currently moving away from Fourier-based analysis and towards classical time-frequency analysis techniques, such as the Scalogram, and Reassigned Scalogram, for the purpose of analyzing low probability of intercept radar signals. Based on the research performed for this paperit was shown that the Reassigned Scalogram by-and-large outperformed the Scalogram for analyzing these low probability of intercept radar signals - for reasons brought out in the discussion section above. More accurate characterization metrics could well translate into saved equipment and lives.

Future plans include analysis of additional low probability of intercept radar waveforms, using additional time-frequency analysis and reassignment method techniques.

References Références Referencias

1. [ANS10] Akansu, Ali N., Wouter A. Serdijn, and Ivan W. Selesnick. "Emerging applications of wavelets: A review." Physical communication 3.1 (2010): 1-18.
2. [ASC16] Apfeld, Sabine, Alexander Charlish, and Wolfgang Koch. "An adaptive receiver search strategy for electronic support." 2016 Sensor Signal Processing for Defence (SSPD). IEEE, 2016.
3. [BOA15] Boashash, Boualem. Time-frequency signal analysis and processing: a comprehensive reference. Academic press, 2015.
4. [CLA13] Clark, Robert M. Intelligence collection. CQ Press, 2013.
5. [COH95] Cohen, Leon. Time-frequency analysis. Vol. 778. Englewood Cliffs: Prentice Hall PTR, 1995.
6. [FAC18] Flandrin, Patrick, Francois Auger, and Eric Chassande-Mottin. "Time-frequency reassignment: from principles to algorithms." Applications in time-frequency signal processing. CRC Press, 2018. 179-204.
7. [GHA20] Ghadimi, G., et al. "Deep learning-based approach for low probability of intercept radar signal detection and classification." Journal of Communications Technology and Electronics 65 (2020): 1179-1191.

8. [GRA11] Graham, Adrian. Communications, radar and electronic warfare. John Wiley & Sons, 2011.
9. [GUT22] Guo, Tiantian, et al. "A review of wavelet analysis and its applications: Challenges and opportunities." IEEE Access 10 (2022): 58869-58903.
10. [HEZ16] He, Zhengyou. Wavelet analysis and transient signal processing applications for power systems. John Wiley & Sons, 2016.
11. [LIX23] Liu, Xinyu, et al. "Lpi radar waveform design with desired cyclic spectrum and pulse compression properties." IEEE Transactions on Vehicular Technology (2023).
12. [MIB16] Mill, Robert W., and Guy J. Brown. "Utilising temporal signal features in adverse noise conditions: Detection, estimation, and the reassigned spectrogram." The Journal of the Acoustical Society of America 139.2 (2016): 904-917.
13. [MIJ18] Mika, Dariusz, and Jerzy Józwik. "Advanced time-frequency representation in voice signal analysis." Advances in Science and Technology. Research Journal 12.1 (2018).
14. [MIL18] Milovanović, Vladimir. "On fundamental operating principles and range-doppler estimation in monolithic frequency-modulated continuous-wave radar sensors." Facta Universitatis, Series: Electronics and Energetics 31.4 (2018): 547-570.
15. [PAC09] Pace, Phillip E. Detecting and classifying low probability of intercept radar. Artech house, 2009.
16. [PRL19] Penedo, Sergio RM, Marcio Lobo Netto, and João F. Justo. "Designing digital filter banks using wavelets." EURASIP Journal on Advances in Signal Processing 2019 (2019): 1-11.
17. [SCH06] Schleher, D. C. "LPI radar: fact or fiction." IEEE Aerospace and Electronic Systems Magazine 21.5 (2006): 3-6.
18. [SHC19] Shi, Chenguang, et al. "Low probability of intercept-based optimal power allocation scheme for an integrated multistatic radar and communication system." IEEE Systems Journal 14.1 (2019): 983-994.
19. [SIA21] Silik, Ahmed, et al. "Comparative analysis of wavelet transform for time-frequency analysis and transient localization in structural health monitoring." Structural Durability & Health Monitoring 15.1 (2021):1.
20. [SKZ21] Sun, Kewen, and Tengteng Zhang. "A new GNSS interference detection method based on rearranged wavelet–hough transform." Sensors 21.5 (2021): 1714.
21. [SON22] Song, Yuxiao, et al. "Ultra-low sidelobe waveforms design for LPI radar based on joint complementary phase-coding and optimized discrete frequency-coding." Remote Sensing 14.11 (2022): 2592.
22. [STO13] Stove, A. G. "Radars with low probability of interception." Прикладная радиоэлектроника 12, № 1 (2013): 114-121.
23. [STS16] Stevens, Daniel L., and Stephanie A. Schuckers. "Low probability of intercept frequency hopping signal characterization comparison using the spectrogram and the scalogram." Global Journals of Research in Engineering 16.J2 (2016): 13-23.
24. [STS17] Stevens, Daniel L., and Stephanie A. Schuckers. "Low Probability of Intercept Triangular Modulated Frequency Modulated Continuous Wave Signal Characterization Comparison using the Spectrogram and the Scalogram." Global Journals of Research in Engineering 17.F2 (2017): 37-47.
25. [VGS17] Vanhoy, Garrett, Thomas Schucker, and Tamal Bose. "Classification of LPI radar signals using spectral correlation and support vector machines." Analog integrated circuits and signal processing 91 (2017): 305-313.
26. [WAL13] Wang, Lu, et al. "Multi-Gaussian fitting for pulse waveform using weighted least squares and multi-criteria decision making method." Computers in biology and medicine 43.11 (2013): 1661-1672.
27. [WIL06] Wiley, Richard. ELINT: The interception and analysis of radar signals. Artech, 2006.
28. [WSQ19] Wang, Shi Qiang, et al. "The background and significance of radar signal sorting research in modern warfare." Procedia Computer Science 154 (2019): 519-523.
29. [YCC14] Yi, Hua, Zhiquan Chen, and Yanhua Cao. "High precision computation of morlet wavelet transform for multi-period analysis of climate data." Journal of Information & Computational Science 11.17 (2014): 6369-6385.
30. [YUG19] Yu, Gang, et al. "Local maximum synchrosqueezing transform: An energy-concentrated time-frequency analysis tool." Mechanical Systems and Signal Processing 117 (2019): 537-552.
31. [ZHF22] Zhang, Dong, and Zhipeng Feng. "Enhancement of time-frequency post-processing readability for nonstationary signal analysis of rotating machinery: Principle and validation." Mechanical Systems and Signal Processing 163 (2022): 108145.
32. [ZML16] Zhang, Ming, Lutao Liu, and Ming Diao. "LPI radar waveform recognition based on time-frequency distribution." Sensors 16.10 (2016): 1682.

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Uncovering the Atlantic Wholesale Electricity Market

By Alexandre Pavlovski

Abstract- To ensure successful steps to a low carbon economy and total electrification, commitments to deep decarbonization in North America require regional power system integration. The most efficient solution for regional power integration, enabling competitive electricity wholesale is proven by Regional Transmission Organizations (RTO). The RTO concept and practices ensure high efficiency and reliability of regional electricity markets and power transmission system operations. To improve power integration of regional and inter-regional electricity trade using an RTO approach, the last frontiers for organized wholesale markets in North America should be identified, addressed and resolved.

One of important frontiers for competitive regional electricity wholesale in North America is presented by Atlantic Canada. An Atlantic RTO (ARTO) here manifests a key upgrade and an important component of the Canadian Electricity System addressing its generation mix, transmission structure and regulatory framework, and advancing inter-regional East-West and North-South power integration. The ARTO would enable best-in-class regulations that strengthen existing policies for the electricity sector and should be seen as a compelling high priority in leveraging the Clean Grid 2035 target in Canada.

Keywords: deep decarbonization, deep integration, regional/inter-regional power integration, regional transmission organization, competitive electricity wholesale market, electricity trade, power transmission, electricity system, power system, energy gateway.

GJRE-F Classification: *LCC Code: HD9685.U5*

UNCOVERINGTHEATLANTICWHOLESALEELECTRICITYMARKET

Strictly as per the compliance and regulations of:

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The ARTO is positioned as a critically important regional integration advancement in Canada's deep decarbonization pathways. Strong connection between Deep Decarbonization and Deep Regional/Inter-regional Electricity Market Integration concepts and practices reinforces the role of the Atlantic RTO in realizing Canada's 2030 Emissions Reduction Plan. It ensures the benefits of electricity market integration in Atlantic Canada such as increased diversity of generation mix, improved system reliability, increased supply security and demand diversity. Prompt deployment and operation of the Atlantic RTO would make the region more competitive nationally and internationally.

Timely coordination and cooperation of the government, private, academic, and civil electricity sub-sectors on multiple levels in the Atlantic region is suggested so as to achieve the ARTO deployment within the 2025-2035 timeframe. As a part of the cooperative action, the ARTO development and deployment would greatly benefit from the existing electricity system operator skillset of the industry in New Brunswick and Nova Scotia. The civil electricity sub-sector should be promptly engaged with deep participation of Canada's First Nations so as to leverage personal, organizational, and societal developments in the region.

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Keywords: deep decarbonization, deep integration, regional/inter-regional power integration, regional transmission organization, competitive electricity wholesale market, electricity trade, power transmission, electricity system, power system, energy gateway.

Graphic Abstract

I. Introduction: Regional Integration as the Way Forward

a) *Regional Power Integration Matters*

Commitments to low carbon economy and adaptation to climate change, requiring total electrification of our society in the 21st century, leveraged the efforts of electricity industry restructuring, strengthening power grid transmission, and regional /inter-regional electricity market integration [1].

Regional power system integration of jurisdictions is a complex undertaking dealing with multi-disciplinary issues, addressing technical, economic, legal, political, social, and environmental aspects involved [2].

The levels of regional power integration include the following key levels [3]:

- *Interconnection:* Initially involves two, and later - more jurisdictions, includes long-term bilateral power purchase agreements (PPA);
- *Shallow integration:* Involves a number of neighboring jurisdictions, includes long-term PPAs supplemented with short-term electricity markets;
- *Deep integration:* Full operation of a multi-jurisdictional interconnected system, enables competition achieved through a range of wholesale markets (e.g., day ahead and a series of real-time auctions, capacity auctions, ancillary services, transmission congestion contracts). Deep integration means comprehensive trade agreements regulating the business environment including competition policy, investor rights, product standards, public procurement and intellectual property rights [4].

Some challenges slowing progress and mitigating the full benefits of deeper integration may include difficulty aligning jurisdictional and regional investment decisions; differences in regulatory environments between jurisdictions; insufficient regional institutions; dearth of financing; changes in political frameworks; and jurisdictional and national sovereignty and energy independence concerns.

However, today regional power system integration within a country (e.g., states or provinces) and/or internationally is clearly understood as a critical, productive and much needed approach, and an important strategy to help provide reliable, affordable electricity to their economies and citizens [3]. Increased electricity cooperation and trade between jurisdictions leading to power sector reform and integration can enhance energy security, bring economies-of-scale in investments optimizing them on a regional basis, facilitate financing, enable greater renewable energy penetration, reduce emissions, ensure technical and regulatory harmonization, and allow for synergistic sharing of complementary resources.

b) Deep Integration means Deep Decarbonization

As a critical component of climate change mitigation, deep decarbonization of electricity will enable a more efficient and rapid transition to a zero-carbon electricity system, and greatly contribute to deep decarbonization of our society [5]. Adopting deep integration at regional and inter-regional level will decarbonize regional power sectors at the lowest overall cost [6]. Improving integration and coordination of electricity systems to achieve deep integration levels and related deep decarbonization goals opens up key opportunities such as the higher potential to integrate renewable energy, and economic efficiency gains [7]. Reaching short-, medium- and long-term targets for GHG emission reduction via clean grid achievements requires urgent policy efforts to accomplish deep regional integration [8].

c) Regional Transmission Organizations Lead

In North America restructuring of the electricity industry to successfully achieve deep regional integration benefits were demonstrated by the formation of Independent System Operator (ISO), and later - Regional Transmission Organization (RTO) solutions [9-12].

ISOs and RTOs are independent nonprofit organizations responsible for grid reliability, planning and competitive wholesale market operations. Roughly two-thirds of the United States and two major provinces in Canada (Alberta and Ontario) today are served by these organizations.

RTOs manage centralized regional markets for electric energy, ancillary services, capacity, and offer financial contracts for hedging congestion risks, while not taking a position in these wholesale power markets. They also manage the joint transmission assets on behalf of a number of transmission-owning electric utilities as their members while not owning any of these assets. RTO markets are independently monitored for market power abuses and manipulation.

RTOs enable the aggregation of generation resources for economic dispatch [9] by having generation resources over a number of utility control areas cost-optimized and dispatched jointly.

Federally regulated RTOs are governed by boards that are independent of any market participants [13].

The benefits of regional grid integration demonstrated by RTO include:

- *Wholesale markets created:* Highly liquid and competitive; this includes high competitiveness of the auction structure;
- *Regional complementarities in demand:* Non-coincident demand provided benefits to regional integration without massive investments in transmission upgrades while systems with highly coincident demands enabled more robust transmission infrastructure to support competition;
- *Efficiencies:* Increased efficiencies of low-cost baseload units in joint regional dispatch;
- *Environmental effects:* More intensive use of lower-cost resources in regional dispatch.

A successful example of using RTO for regional grid integration in North America is shown by New England. The New England States Committee on Electricity (NESCOE) representing the collective perspective of the six New England Governors in regional electricity matters, used ISO New England (ISO-NE) as a vehicle for government level planning and policy coordination. With technical coordination provided by ISO-NE NESCOE advanced the New England states' "common interest in the provision of electricity to consumers at the lowest possible prices over the long-term, consistent with maintaining reliable service and environmental quality" [14].

As the initial ISO-NE's mission and governing structure were established in mid-1990ies, New England's existing wholesale electricity markets are currently being modernized to support achievement of clean energy laws, while maintaining system reliability and fostering more affordable electricity for regional consumers. Today the New England States are committed to pursuing a new, regionally based market framework meeting the States' decarbonization mandates and maintaining resource adequacy at the lowest cost by using market-based mechanisms [15]. An example of the current regional wholesale market upgrade is a New England Forward Clean Energy Market (FCEM) [16,17], a centralized auction market that allows multiple bidders, including states and other entities, to purchase a variety of clean energy products from suppliers across New England. This includes transmission system planning to unlock onshore wind resources located far from load centers, to integrate significant levels of new offshore wind resources and new hydro resources, and to facilitate widespread adoption of DERs.

d) Levering the Atlantic Energy Gateway Initiative

While Atlantic Canada and the northeastern US are bound together by natural economic ties, these regions are divided by a border which limits the development of transport and energy infrastructure and does not support the high degrees of economic integration and business co-operation that characterize the continent's key economic regions [18].

To address this major issue at a business community level, national and international discussions addressing this gap were made in 2004 [18-20]. The concept of Atlantica: the International Northeast Economic Region brought together Atlantic Canada; Maine, New Hampshire, Vermont, and upper state New York; as well as southeastern Quebec to enable full participation of these three areas in the North American growth strategy [18, 21]. The Atlantica region was defined chiefly by geography, economic trends and trade patterns; common problems and experiences; and politics.

To enable a significant competitive advantage of Atlantica in the continental and global economies of the future, new forms of overarching co-operation were requested to ensure that "goods, services and people can flow easily and efficiently to the places where the most value can be added to them".

Specifically, the Atlantica region discussions addressed a growing awareness of the importance of regional co-operation in energy, the value of electricity as a unique tradable commodity produced and consumed instantly, and regional power grid issues. An innovative mechanism to create a wholesale market was proposed based on a "natural benefit" for Atlantica. The region was seen as primed for the development of a competitive regional market for electricity, and "the adoption of identical laws in each participating province and state was required with more coordination and uniformity among regulatory authorities" [20, 22].

This effort was further promoted in the Atlantic Gateway and Trade Corridor Strategy, developed jointly by the governments of Canada and the provinces of Nova Scotia, New Brunswick, Prince Edward Island and Newfoundland and Labrador [23-25]. The Atlantic Gateway Memorandum of Understanding (MOU) of October 2007 directed the development of an Atlantic Gateway strategy that would benefit the Atlantic region and Canada through economic growth, increasing international trade and enhancing Canada's competitive position in the global economy. This included a current thrust to grow the energy sector by focusing on generating and exporting electricity from renewable sources, including hydro, wind, tidal, nuclear and biofuels.

Specifically, to leverage clean electricity, the Atlantic Energy Gateway (AEG) initiative was announced in March 2009 to enhance regional co-operation towards the development of Atlantic Canada's clean energy resources [26,27]. With emerging clean electricity opportunities in the region from large hydro, wind and tidal power, and green hydrogen production development, the Atlantic Energy Gateway was clearly seen as one of the strategic gateways to prosperity in Atlantic Canada and beyond [28-31].

The foundations for regional collaboration and planning through the AEG initiative by March 2012 contributed to the following decade of changes defined in the Clean Power Roadmap for Atlantic Canada [32,33] and further shaped by the Government of Canada's commitment to achieve an emissions-free grid ("Clean Grid") by 2035. By fully decarbonizing Canada's electricity grids, the country is enabling the rest of the economy to electrify by 2050 [34-37], and regional grid integration in Atlantic Canada is expected to contribute to effectively meeting the Clean Grid requirements for each of the utilities in the region.

e) Regional Wholesale Market: Advancing a Strategic Step

Addressing the regional wholesale market needs, Nova Scotia demonstrated its leadership in the Atlantic region starting its Energy Reform 2024 as a potential "prelude" to an Atlantic wholesale market operated by an ISO/RTO in the region.

New legislation introduced on February 27, 2024, allowed for modernizing Nova Scotia's electricity system and enhancing public utility regulation in the energy sector [38,39]. The new legislation changed the way the electricity system in Nova Scotia is structured and regulated, making it more accountable, transparent and competitive by creating an independent energy system operator ("IESO") responsible for the oversight of wholesale market rules, interconnections, system planning and procurement. This decision supported continuing strong efforts of Nova Scotia's government to ensure provincial ratepayers have clean, reliable and affordable electricity.

Based on this decision, the wholesale market needs, the sources and experience with Newfoundland and Labrador, and socio-economic studies of a proposed DC grid from Sable Island offshore wind area to New England will define the requirements to and the skills of the IESO.

As Nova Scotia (and any province in Atlantic Canada) is too small to have their stand-alone wholesale electricity markets function competitively and efficiently in North America, a prompt next step may have to be made to advance regional grid integration opportunities by establishing a Regional Transmission Organization in Atlantic Canada to provide a much higher wholesale electricity level to play [20]. Such an Atlantic RTO representing the next phase of market restructuring in the region will present a critical opportunity for becoming a broad, regionally integrated wholesale electricity market player operating together with NYISO and ISONE in the American Northeast. This strategic step can lever the value of inter-regional coordination and transmission in decarbonizing the electricity industry and contributing to the clean electrification of low carbon economies in North America.

II. Materials and Methods

a) RTO as a Deep Integration Toolset

The electricity industry has long been dominated by monopolies, but most of the historical justifications for monopoly no longer apply [13]. Regional solutions for transmission grids and wholesale electricity markets in North America represented by Regional Transmission Organizations (RTO) have been demonstrating substantial and well-documented benefits to the areas they service, including lower costs, improved reliability, and better environmental performance. The advantages brought by RTO make it a compelling option for the regions not yet served and trying to reshape their electricity landscapes; as a result, the areas serviced by RTO are continuously growing [13, 40].

i. *RTO History*

Historically, wholesale electricity sales developed over time by jurisdictional utilities - regulated monopolies given rights to own and operate transmission and distribution networks in a given geographical area along with the responsibility to serve all loads in that same area [41]. These utilities were vertically integrated, owning the generation, transmission and distribution systems, and were responsible for the entire flow of electricity to consumers [42, 43].

The Energy Policy Act of 1992 (EPAct) [44] laid the initial foundation for the eventual deregulation of the North American wholesale electricity market. This Act called for utility companies to allow external entities fair access to the electric transmission systems. The act's intent was to allow large customers (and in theory, every customer) to choose their electricity supplier and subsequently pay for the transmission to deliver it from the generation to serve their load [42-44].

To satisfy the requirement of providing non-discriminatory access to transmission and open the wholesale electricity market to competition, in April 1996 the Federal Energy Regulatory Commission (FERC) issued two orders that changed the landscape of how electricity is generated, transmitted, and distributed throughout the North America [10,11].

Order No. 888 (the "Open Access" order) defined its primary objective to establish and promote competition in the generation market, by ensuring fair access and market treatment of transmission customers. Among the key points outlined by FERC to accomplish this goal the Commission required all jurisdictional utilities within the U.S. to file an open-access transmission tariff (OATT) and promoted the concept of forming Independent System Operator (ISO) organizations at the direction or recommendation of FERC to coordinate, control, and monitor the operation of the bulk power system, and administer wholesale electricity markets within their areas of operations.

Order No. 889 (the "Standards of Conduct" order) defined in detail exactly how all participants in the electricity market should interact with transmission providers.

In December 1999 FERC followed up with its Order No. 2000, encouraging the voluntary formation of Regional Transmission Organizations (RTO) to administer the transmission grid and wholesale markets on a regional basis in a larger geographic area throughout North America (including Canada).

FERC's Orders No. 888, 889 and 2000 brought strong support from the power industry. As of today, there are nine ISO/RTO organizations operating in North America [12] and using competitive market mechanisms that allow independent power producers and non-utility generators to trade power.

In the U.S., six of these organizations: Southwest Power Pool, Inc. (SPP), PJM Interconnection, LLC (PJM), New York Independent System Operator, Inc. (NYISO), Midcontinent Independent System Operator, Inc. (MISO), ISO New England Inc. (ISO-NE), California Independent System Operator Corporation

(CAISO) are subject to the FERC's jurisdiction under sections 203, 205, or 206 of the Federal Power Act. The seventh - The Electric Reliability Council of Texas (ERCOT) serving as an independent system operator within the Texas Interconnection, which is not synchronously interconnected with any other interconnection in North America, is not subject to the FERC's jurisdiction.

In Canada there are two ISO organizations: Alberta Electric System Operator (AESO) serving the province of Alberta, and Independent Electricity System Operator serving the province Ontario.

Fig. 1.1: ISO/RTO in North America [12]

Fig. 1.1 indicates what areas in North America are covered/serviced by RTO, and what areas (shaded in grey) are not serviced.

The major functions of RTO are administering competitive wholesale markets, and transmission services operations and planning.

ISO, RTO, and ISO/RTO acronyms in publications are often used interchangeably. The only difference between an ISO and an RTO is the size of its footprint (e.g., ISO for servicing one jurisdiction vs RTO for regional service) and the way it prices its services.

ii. *RTO Market Values*

Wholesale Electricity Markets provide multiple benefits to customers and to the grid. A definition of the market value is clearly presented by an Independent Electricity System Operator covering the province of Ontario, Canada [45]:

- *Markets enhance reliability:* 'When system-wide problems do arise, RTOs enhance rather than detract from reliability. They have superior situational awareness over a wider area than is possible for a single utility, so when challenging weather conditions occur or a large generator unexpectedly drops out of service, an RTO will know which generation and transmission resources are available to respond immediately. Although all utilities have contingency plans to maintain service during unexpected events, RTOs' access to a wider range of resources over a broader area offers a greater level of adaptability to more extensive issues, like when a weather event threatens large states or multiple states at once" [13].
- *Markets drive economic growth:* By offering opportunities for suppliers to earn profits, markets drive job creation and economic growth. Markets also make the pricing of electricity more transparent.
- *Markets improve grid operability:* Since electricity suppliers are only paid when they produce electricity, markets encourage suppliers to operate

within their limits. If suppliers are unable to supply electricity at any given time, they lose revenue.

- *Markets level the playing field:* By giving new market entrants a baseline for their decision-making.

RTO administer and evolve regional electricity markets in order to foster competition among suppliers and ensure fair and affordable pricing for ratepayers, which in turn drives innovation. As thoughtfully mentioned in [13], "Power generation and wholesale transmission operations are not natural monopolies; they are structurally competitive. The evidence from more than 20 years of RTO experience in Texas and the East shows that market competition has led to more efficient generator operations and better investment decisions. Without the guaranteed returns managed by monopoly utilities, market participants are more prudent in their spending and risk management".

"The economic and reliability advantages of RTOs are well documented and explain why consumers with growing electricity needs are at the forefront of promoting RTO expansion. In addition, many stakeholders favor RTOs for their environmental benefits, including accelerating clean investment that both displaces legacy fossil resources and better integrates renewable energy resources into the grid" [13].

iii. *RTO Products and Operations*

RTOs have been discreetly described as an "air traffic control" system for the electric grid [13]. Indeed, "RTOs do not own electric generators or transmission wires, nor do they buy or sell electricity. Instead, they oversee the flow of electricity over the transmission system, ensuring that the amount of electricity generated and consumed stays in balance and that no component of the grid gets overloaded. Thus, the core task performed by RTOs is coordinating electricity power flows from producers to consumers in ways that minimize costs and respect the limits of the grid, and in so doing, help avoid blackouts and other problems."

RTOs benefit from their regional footprint which is much broader than a footprint of each utility when there is a need to address any external forces on the grid outside of an individual utility's control. This allows for enhancing RTO's ability to coordinate power production and consumption in advance of impending or unforeseen issues and keep the system working smoothly.

Today's RTOs operate on a system known as "security constrained, bid-based, economic dispatch." "Security constrained" refers to ensuring that power flows stay within safe operating levels. "Bid based" indicates that the system primarily relies on generator owners' voluntary offers to increase or decrease output. "Economic dispatch" indicates that the RTO seeks to minimize the overall cost to consumers by prioritizing the use of the lowest-cost generation resources available.

The "bid-based economic dispatch" part of the RTO system design works to find the cheapest-available generators to manage grid congestion. Before the day begins, an RTO's day ahead market enables the scheduling of the lowest-cost resources available capable of meeting forecasted demand consistent with safe, reliable operation of the grid. In real time, the RTO will update its economic dispatch every 5-10 minutes based on changes in consumption and production on the system, issuing instructions to generators to increase or decrease their output in consideration of grid limits, making the adjustments in the lowest-cost way as determined by generator offers into the system.

In addition to Energy Market with a day-ahead auction and a series of real-time auctions, RTOs offer other three market elements [46]:

- Ancillary Services and Operating Reserves Market providing flexibility and supporting robust transmission operations,
- Capacity Market addressing resource adequacy needs, and
- Transmission Congestion Contracts Market addressing locational price risks.

iv. *RTO Independence and Governance*

a. *RTO Board Structure*

Across the country, ISO/RTOs are governed by boards of directors whose members vary in number from 5 to 10. In general, a nominating committee identifies new board members and their appointment is ratified by either a vote of the ISO/RTO's members (e.g., PJM, MISO and SPP) or by a vote of the board (e.g., ISO-NE, NYISO). In contrast, the board members of the California Independent System Operator (CAISO) are nominated by the Governor of California and confirmed by the California State Senate - see *Table 1.1* for details.

Table 1.1: ISO/RTO Governing Entities (see Table 1 in [40])

ISO/RTO	Governing Entity	Composition	Board Member Selection
CAISO	Board of Governors	5 members	Nominated by Governor of California and confirmed by state senate.
ISO-NE	Board of Directors	9 independent directors plus president/CEO (non-voting.)	Slate nominated by a committee of NEPOOL and NECPUC. Final vote by board.
MISO	Board of Directors	9 independent directors plus president/CEO (non-voting.)	Identified by Nominating Committee, selected by board, and voted on by Members.
NYISO	Board of Directors	10 directors including president/CEO.	Identified by Stakeholder Management Committee, nominated by Governance Committee, and elected by board.
PJM	Board of Managers	9 voting managers plus PJM president (non-voting.)	Selected by Nominating Committee and elected by Members Committee.
SPP	Board of Directors	9 independent members plus the SPP president (non-voting on most matters).	Candidates nominated by Governance Committee and elected by members.

Source: Adapted from CAISO Summary of ISO/RTO Governance Structures, October 2014.

The RTO Board structure defines whether the decision-making responsibility is "done centrally" or "divided among many individuals." It also determines who will be held accountable when "things go wrong".

Today, the governing board of a new RTO may consider a mix of stakeholder and independent directors in an effort to address these issues provided the rules prevent any one stakeholder sector from gaining too much influence.

Jurisdictional (state or province) participation in RTOs does require a commitment of resources. Typically, a commissioner from each jurisdiction is assigned to serve on a market advisory committee. Jurisdictional participation also brings benefits as its planning, reliability and environmental policies can be met at lower costs to consumers when participating in a well-designed RTO.

b. *Jurisdictional Policy Autonomy*

Several practical concerns emerge from the political differences across jurisdictions participating in an RTO. E.g., "politically conservative U.S. states worry that joining an RTO with a more politically progressive state may result in conservative state consumers subsidizing progressive state policies, particularly those related to clean energy mandates and other environmental goals. Conversely, some in progressive states are concerned that their policy goals might be hindered if they participate in a regional market with more conservative states. Both types of concerns amount to the desire that the state retain control over its own energy policy choices, especially their preferred generation mix" [13].

c. *Managing the Costs of Market Seams*

A power system seam is a difference in the methods, rules, or designs of power system operations that can create transaction costs or externalities when crossing market boundaries [201].

RTOs dedicate significant resources to solving seams issues. The five key inefficiencies associated with power market seams within an RTO were summarized in [13] as follows:

1. Ineffective interregional transmission planning
2. Generator-interconnection delays due to information -sharing requirements
3. Reduced resource adequacy capabilities
4. Difficulty in managing unintended power flows
5. Inefficient trading across lines connecting two markets

Currently, increasing market efficiency can be achieved by intertie optimization [47]. Intertie optimization adjusts power transfers between two markets—that is, on lines connecting the two markets—in ways that maximize the use of the lowest-cost energy available in either market, or in ways that are always consistent with safe operating levels on the grid.

Now, with a better understanding of RTO principles, let's look attentively at RTO experiences in the U.S.

b) Experiences of Regional Transmission Organizations

i. *RTOs in the American Northeast*

Regional Transmission Organizations (RTO) in the American Northeast: NYISO and ISO-NE administer the region's wholesale markets, plan the transmission system, and operate the power system through collaboration and innovation to ensure reliable and competitively priced wholesale electricity is always available [48].

For over 20 years the RTOs have been consistently demonstrating that "competitive electric markets continue to provide the most powerful and least-cost vehicle available" [49]. These wholesale electricity markets are used as an important regional development tool to attract necessary investments to facilitate the transition of the grid in the coming decades.

With public policies in the Northeast increasingly prioritizing clean energy production and a rapid transition away from fossil fuels, the RTOs address policy-based, societal, or extreme weather challenges through maintaining adequate supply necessary to meet growing consumer demand for electricity, and strengthening electric system reliability as the top priority.

Responding to public policies in their regions that are driving rapid change in the electric system, and impacting how electricity is produced, transmitted, and consumed, the RTOs in the Northeast have been successfully addressing critical strategic issues including:

- Higher projected demand driven by Electrification programs and economic development initiatives,
- Expected changes in electricity peaking driven by electrification of space heating and transportation,
- Interconnection processes balancing generation developer flexibility with the need to manage the process to more stringent timeframes,
- Timely construction of new supply and transmission to support reliability of the grid,
- Increased dependence on variable renewable resources and batteries, and
- New emission-free resources needed to meet the regional goals.

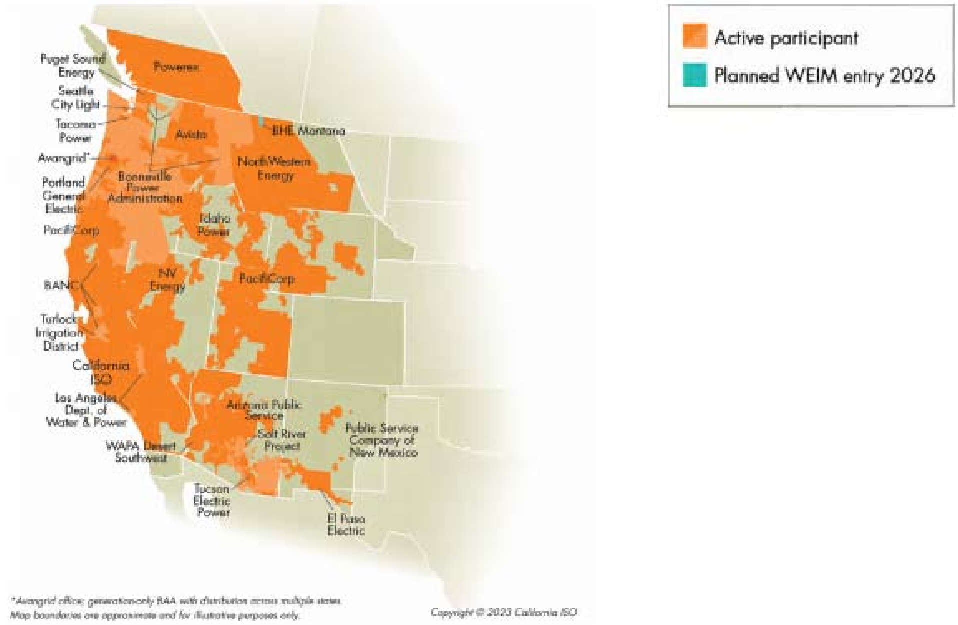
Through necessary studies supporting and contributing to the power grid evolution towards the grid of the future the RTOs are continuously exploring the next steps for their 2035, 2040 and 2050 targets in competitive wholesale markets, transmission, reliability, operations, extreme weather events, and new technologies.

Specifically, ambitious market targets to reduce GHG emissions from economic activity throughout the economy are being considered (e.g., [50] including Forward Clean Energy Market ("FCEM"), compensating non-emitting resources via the development of a centralized, forward market for clean energy, with the corresponding costs allocated to electricity consumers; Net Carbon Pricing ("NCP"), pricing carbon emissions from generators and returning the carbon price revenues to electricity consumers; and Hybrid approaches combining FCEM and NCP.

Examples of innovative efforts in the Clean Energy Transition helping the RTOs adapt to evolving technologies and system conditions [48] include Inverter-Based Resource Integration and Modeling capturing the unique performance characteristics of inverter-based resources (e.g., solar and wind), and Integrated Market Simulator to better and more cost-effectively quantify the potential outcomes of future market design changes or potential changes in system supply and demand conditions.

ii. *The RTO West Concept*

Positive experiences in the West are presented by real time power markets: the Western Energy Imbalance Market (WEIM) operated by California ISO (CAISO), launched in 2014 for participating utilities outside of the CAISO region [51] (see *Fig. 2.1* below), and a similar Western Energy Imbalance Service market (WEIS) operated by the Southwest Power Pool (SPP), launched in 2021 for other utilities in the West [52]. The current work being done to improve both the WEIM and WEIS by introducing day-ahead markets has strongly driven the concept of a West-wide RTO (or possibly two RTOs [13]) within the next few years.

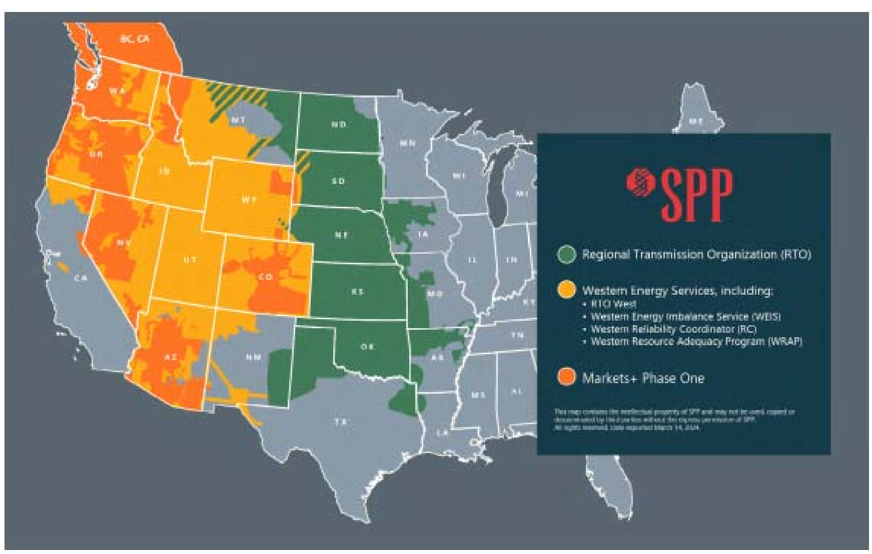


Source: "About," CAISO, last accessed July 17, 2024. https://www.westerneim.com/Pages/About/default.aspx.

Fig. 2.1: Western Energy Imbalance Market (WEIM) administered by CAISO

A part of this concept is related to improving regional resource adequacy and transmission with planning efforts in the western United States.

Besides the CAISO and SPP efforts towards an RTO West, related initiatives were presented by the Western Resource Adequacy Plan (WRAP), the Western Transmission Expansion Coalition (WestTEC), and the West-Wide Governance Pathways Initiative (WWGPI).



Source: "RTO Western Marketplace Map," Southwest Power Pool, last accessed July 17, 2024. https://www.spp.org/media/2072/rto-wes-marketsplus-map.jpg.

Fig. 2.2: SPP Proposal: Western Energy Services and Markets+

Specifically, most competitive today offering to provide an RTO in the Western Interconnection is presented by Markets+, a conceptual bundle of services proposed by SPP. Markets+ would centralize day-ahead and real-time unit commitment and dispatch and pave the way for the reliable integration of a rapidly growing fleet of renewable generation [53]. SPP filed its Markets+ tariff (the proposed market rules) with FERC in April 2024, and a decision by FERC is expected later this year. In June 2024, SPP proposed changes to its RTO tariff to enable full membership in the RTO for utilities in the Western Interconnection. Several small- and medium-sized utilities in the West have expressed interest in joining SPP as soon as early 2026.

As summarized in [13], "Establishing core RTO functions, namely those around organized markets and regional transmission planning and cost allocation, is a proven, equitable approach that has been shown to advance the core electricity objectives of both progressive and conservative states: lower costs, greater reliability, and environmental benefits. If the states in the West are able to embrace the idea of an RTO (or two) and work toward implementation, they will be on the most promising path for establishing a more comprehensive, efficient, and dynamic system of wholesale electric competition in the region".

iii. *Southeast Problems*

The Southeast stands apart from the rest of the nation for its lack of any kind of regional competitive wholesale electricity market independent of incumbent vertically integrated utilities [54,60]. While two-thirds of electricity consumers in the United States live in a region with organized competitive wholesale power markets operated by a Regional Transmission Organization or Independent System Operator (RTO/ISO), and with much of the West being currently part of real-time Energy Imbalance Markets administered by CAISO and SPP and moving promptly to an RTO solution, the Southeast largely retains the decades-old vertically integrated utility model, with each utility separately operating its own generating resources and transmission system.

While utilities in the Southeast are interconnected and there is limited trading of wholesale electricity between them, they each continue to rely almost exclusively on their own generation resources to meet customer needs.

Continuing with business as usual means the risk of generation overbuild is high and increasingly expensive [55]. To bring public attention to values and merits of an RTO in the Southeast, approaches to competitive pricing across the Southeast had been presented [55-57]. The analysis forecast the considerable positive impacts of a seven-state wholesale electricity market being set up in 2025, spanning Alabama, Florida, Georgia, Mississippi, North Carolina, South Carolina and Tennessee [58].

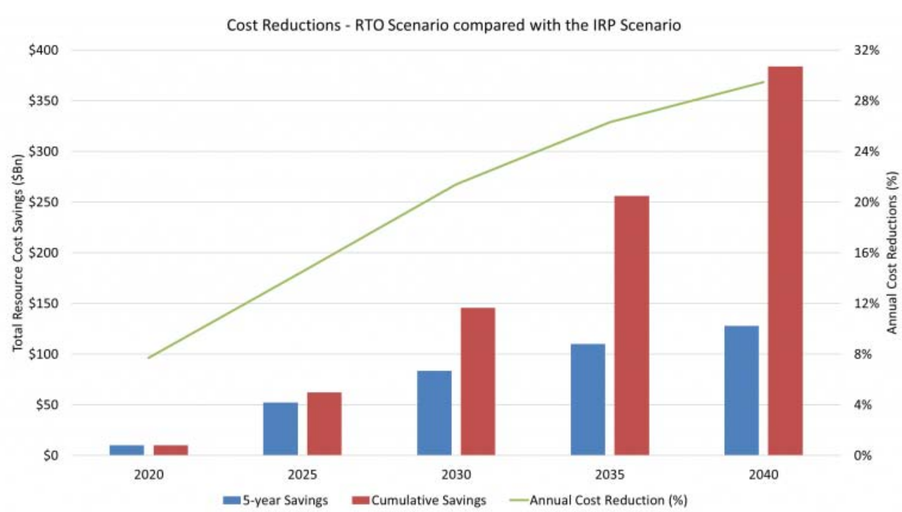


Fig. 2.2: Competitive Southeastern RTO economic savings scenario [58]

Seeing potential RTO benefits, Southeastern states started exploring ways to bring competition to the region's wholesale markets; e.g., the South Carolina legislature passed and the Governor signed Act No. 187 of 2020, which created an Electricity Market Reform Measures Study to consider establishing or joining a broader regional wholesale market such as an RTO or energy imbalance market [59].

However, in February 2021 a group of utilities including Duke, Dominion Energy South Carolina, Southern Company, Associated Cooperative and the Tennessee Valley Authority, submitted filings to FERC asking to approve a Southeast Energy Exchange Market (SEEM) – a regional energy market in the Southeast U.S. that uses a centralized intra-hour energy exchange to create bilateral trade among its trading participants every 15 minutes. SEEM presented a real-time market including Dominion Energy South Carolina, Duke Energy Carolinas, Southern Co. and 21 other participants [66,67].

Global Journal of Research in Engineering (F) XXIV Issue I Version I Year 2024

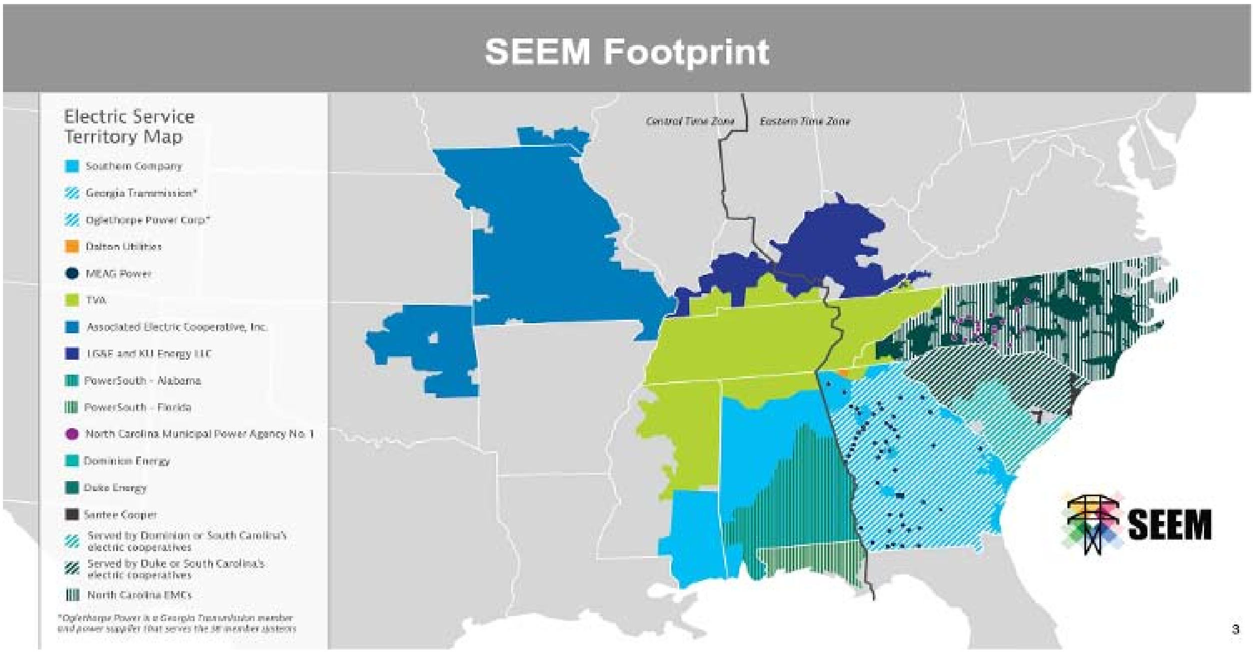


Fig. 2.3: Southeast Energy Exchange Market (SEEM) [54]

In its filings to FERC SEEM was described not as an RTO/ISO, nor was it analogous to the EIM administered by CAISO or SPP. It just bore few similarities to other structural options for wholesale energy markets, and took only very small competitive steps away from the vertically integrated status quo compared to the integrated RTO practice (see Fig. 2.4):

Fig. 2.4: Structural Options for Regional Wholesale Markets [54]

According to the prompt and clear SEEM critics, "With few non-utility generators able to operate in the region today and no clear path for them to join SEEM, the end result of the process is this: if no utility is offering excess generation, no utility is seeking additional generation, and no transmission capacity is sitting idle, no deal – and no savings for customers, even if in a competitive market such opportunities would be revealed. …That this approach to power trading would serve utility interests above all" [60]. The critics argued that the benefits of SEEM are "paltry compared to a full organized market and that the proposal lacks the independence and robustness needed to deliver benefits to consumers" [61].

In March 2021 a number of public interest organizations filed a protest asking the FERC not to approve SEEM [62,63]. However, after the SEEM applicants' response to two FERC's extensive deficiency letters and the FERC deadlocked 2-2 commissioners vote SEEM was allowed to take effect due to rules regarding tie votes by the agency as it "became effective by operation of law" because of the "absence of Commission action on or before October 11, 2021" [64-66]. While SEEM started its operations in November 2022 [67], in July 2023 a federal appeals court agreed with the critics, invalidating SEEM on the grounds that it violates federal regulations that require open access to such markets [61]. It addressed the key issue: while SEEM would be convenient for utilities, its limited structure would have provided little to no benefits to consumers. SEEM's participation requirements also unfairly discriminate against non-utilities that do or may have ongoing bilateral trading relationships with SEEM members but are ineligible to participate in the SEEM exchange. Following an appeals court ruling, the Federal Energy Regulatory Commission is reconsidering its approval of the Southeast Energy Exchange Market [68, 69]. At the same time, several states in the Southeast already started exploring full RTO membership.

Now having summarized RTO experiences in the U.S. in the end of 2024, let's review is today's contribution into regional integration in North America enabling its deep decarbonization.

c) *Regional Power Integration for Deep Decarbonization*

i. *Leading on Deep Decarbonization Pathways*

Deep Decarbonization Pathways (DDPs) are seen today as "sector-by-sector blueprints of changes over time in physical infrastructure such as power plants, vehicles, buildings, and industrial equipment—that inform decision makers about the technology requirements and costs of different options for reducing emissions" [70].

All deep decarbonization pathways incorporate "three pillars" of energy system transformation: energy efficiency and conservation, decarbonizing electricity and fuels, and switching end uses to low-carbon supplies. They present the process of improving infrastructure over time by replacing inefficient and carbon-intensive technologies with efficient and low-carbon technologies that provide the same (or better) energy services.

Canada's deep decarbonization pathways [71] present best-in-class regulations that strengthen existing policies for the electricity, buildings and transport sectors, including enhanced electric grid flexibility and storage to handle more intermittent renewables. Fuel switching to decarbonized electricity is the single most significant pathway toward achieving deep emissions reduction globally. However, to minimize both climate and economic risks, in Canada "we need to become global leaders in decarbonization policy and innovation in these sectors, not laggards" [71]. Canadian Electricity System playing a critical and very important role within the context of Deep Decarbonization, presents a critical priority in shaping its pathways.

ii. *Optimizing Canadian Electricity System*

a. *Realities of Canadian Electricity System*

An excerpt from a report prepared for Electricity Canada [72] defines Canadian Electricity System today as follows:

"The Canadian electricity sector is unique in generation mix, geography, and regulatory structure when compared with other North American jurisdictions. Regulation of the sector takes place at the provincial level with limited regulation of transmission lines that cross provincial boundaries. Except for Alberta, vertically integrated utilities develop the provincial transmission grid and generation resource mix to benefit the province and ratepayers as much as possible. In Alberta, transmission and distribution functions are provided by unbundled utilities and generation is provided in a competitive, energy-only market.

Given the provincial boundaries in Canada, the abundance of vertically integrated utilities, and the nature of regulation, transmission in provinces has largely been focused on North to South corridors connecting resources to load centers within each province, and from provincial load centers to US load centers on the other side of the border. Some connectivity exists between provinces; however, these connections are generally small relative to the size of the markets being connected. In addition, most extra-provincial interconnections have focused on international trade with the US as opposed to a trans-Canadian network. This is again a function of Canadian geography in that Canadian load centers are often much closer to US load centers on the other side of the international border than they are to other Canadian load centers in neighboring provinces.

Most Canadian provinces operate nearly as islands, with limited connectivity amongst Western Provinces (BC, Alberta, Saskatchewan, and Manitoba) and similarly limited connectivity between the Eastern Provinces (Ontario, Quebec, and Atlantic Canada).

Canada's generation mix is also unique with roughly 60% of electricity generation coming from hydroelectric sources. B.C., Manitoba, Quebec, Newfoundland and Labrador, and Yukon all generate over 80% of their electricity from hydropower, while Alberta, Saskatchewan, and Nova Scotia primarily generate their electricity from fossil fuels."

Global Journal of Research in Engineering (F) XXIV Issue I Version I Year 2024

b. *Investments in the Grid a Priority*

Reaching net-zero grid emission by 2035 and net-zero economy-wide emissions by 2050 to realize Canada's decarbonization ambitions requires initial investments focused on the electricity sector. Interconnected regions will play a crucial role in achieving net-zero in Canada. To ensure deep decarbonization transition, it is imperative that investments in the planned renewable generation and storage are optimized across jurisdictions using transmission upgrades. Addressing the uniqueness of the Canadian electricity system, its geography and provincial regulatory structure, a set of general recommendations in a report [72] commissioned by Electricity Canada in 2022 was as follows: (1) develop a clear inter-provincial planning process involving provinces, the federal government, and the First Nations; (2) establish a fair and reasonable cost allocation methodology to be used across Canada; and (3) to continue to explore Canada – U.S. transmission development that can provide financial benefits to Canada.

While Canada's electricity sector is backed by zero emission dispatchable hydroelectric and nuclear resources playing a central role in the country's current transition to a low emission economy, making next steps in deep decarbonization objectives requires major investments in new electricity infrastructure across the country.

As of 2022, while investment conditions at an aggregate level were perceived as favourable, they were patchy across provinces and technologies. Overall conditions for investment are relatively positive for nuclear power generation and for newer technologies such as smart grid and energy consumption management, but less so for renewable and hydrocarbon power generation [73]. Also, while public policy factors overall had a neutral impact on investment decisions, provincial regulatory frameworks for the electricity sector were viewed as having a somewhat negative impact. This highlighted the need for a strategic and coordinated approach to developing electrification policies, both within and between provinces, as well as strengthening regulatory conditions within all parts of the electricity sector value chain.

c. *Recommended Framework for Inter-Regional Grid Infrastructure*

To lead on Canada's Deep Decarbonization Pathways, a collaborative framework to identify and financially support inter-regional electricity transmission projects was recommended by the Canada Electricity Advisory Council in 2024 [74] to outline their governance, cost allocation, and funding components. The European Union's Projects of Common Interest (PCIs) framework [75, 76] was proposed as a starting model.

iii. *Strengthening Inter-Regional Ties*

a. *Inter-Regional Power Sector Integration in the Northeast*

An inter-regional integration approach for the North American Northeast (New York, New England in the Unites States and the Canadian provinces of Ontario, Québec and Atlantic Canada) leading deep decarbonization efforts in the power sector at the lowest overall cost was strongly promoted (e.g., [6]). Gains from such an inter-regional approach were seen critical due to the large amount of hydropower and reservoirs in Canada, which could be used to balance non-dispatchable renewable generation. The related aspects highlighted potential increase of transmission capacities between sub-regions, and coordination of capacity constraints (e.g., planning for available regional capacity instead of relying exclusively on the local generation capacity to meet peak demand, thus avoiding unnecessary peak capacity "duplication").

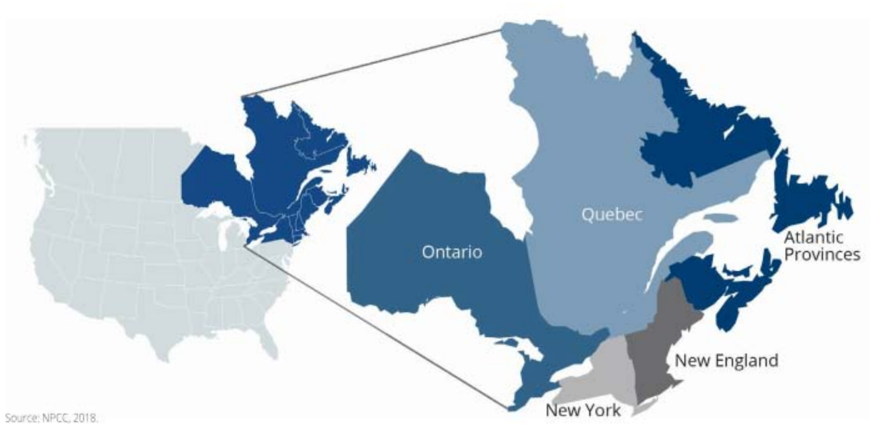


Fig. 3.1: Map of the region overseen by the Northeast Power Coordinating Council (NPCC)

With the electricity sector playing a central role in decarbonization, better coordination in planning and operating the Northeast electricity sector could greatly facilitate GHG emission reduction through the dual challenge of electrifying many energy needs and decarbonizing electricity production. However, "Despite putting forward several ambitious GHG reduction and renewable deployment targets, policy efforts by subnational jurisdictions across the Northeast are falling short, and prospects for meeting renewable penetration levels required by long-term targets appear dim" [8].

To ensure significantly more attention to adjusting and upgrading electricity sector integration strategies across the region focused on variable renewable generation challenges, increased coordination and collaboration among adjacent jurisdictions is seen as immediate and critical. This involves different integration aspects such as physical infrastructure (e.g., interties - connections allowing electricity to flow between power systems), institutional and regulatory cooperation and harmonization (e.g., shared regulation, market design, and systems operation rules), and commercial integration (e.g., level of trade).

According to [8], to achieve such coordination and collaboration, significant institutional, political and social barriers must be overcome:

- Institutional barriers imply a need for subnational jurisdictions to give special attention to regulatory discrepancies across jurisdictions (e.g., market access or price levels). This is necessary to ensure that regional collaboration leads to a streamlining of efforts to harmonize and facilitate integration of grids across subnational jurisdiction borders.
- Political barriers often take the form of combining renewable deployment efforts with local industrial policy and job creation objectives.
- Social barriers materialize through opposition to projects (e.g. wind farms, dams, transmission lines). A viable path to regional integration must consider both the legitimate concerns in local areas and the regional goals to accelerate renewable energy deployment.

Strengthening regional collaboration through additional dialogue, sharing of information and data, and further technical and economic studies on the gains of and approaches to greater integration was seen as a largely recognized next step toward addressing these barriers."

This approach aligns with a broader vision of the U.S. inter-regional transmission expansion and coordination of planning and dispatch for renewable-energy integration [5, 77, 197, 202].

b. *Two-way Electricity Trade Vision*

Related studies promoting the benefits of inter-regional coordination in the Northeast showed a clear move from historical electricity export from Quebec to a "two-way electricity trade" vision.

An example of expanded inter-regional coordination with Hydro-Québec (HQ) for deep decarbonization in the Northeastern U.S. is presented in a related Deep Decarbonization Pathways study [78]. HQ for many years has been playing an important role in Northeast as a key electricity exporter, and there is a significant new resource potential for onshore wind and hydro at relatively low cost within close geographic proximity to the American Northeast. The existing transmission capacity benefits both the Northeast and Québec as it allows south to north exports at certain times during the year in combination with the predominantly north to south flow, keeping transmission utilization rates high. The HQ system, with its large reservoir capacity, has the latent flexibility to provide balancing on both a daily and seasonal scale.

The economic benefits of expanded coordination derive primarily from operating HQ's system as a "regional battery" with extensive south-north as well as north-south flows. This takes greater advantage of the flexibility of the HQ reservoir system and is an expected departure from the longstanding business model of "fixed schedule" HQ electricity exports.

The inter-regional system modeling indicated the daily pattern becoming more dynamic, with exports ramping down during sunrise and ramping up during sunset. This pattern reflects the high levels of solar PV generation in the American Northeast, with HQ importing electricity from the Northeast during daylight hours, particularly during the spring and summer, decreasing HQ hydro generation and increasing reservoir storage.

Another related study [77] concluded that in a low-carbon North American Northeast's future, it is optimal to shift the utilization of the existing hydro and transmission assets away from facilitating one-way export of electricity from Canada to the U.S. and toward a two-way trading of electricity to balance intermittent U.S. wind and solar generation.

For Northeastern U.S. states, a solution based on existing technology was proposed for the use of hydropower reservoirs in neighboring Quebec:

- The optimal use of U.S.-Canadian transmission lines will change drastically the role of Quebec hydro as a generation resource in Northeastern power systems as Northeastern states decarbonize their power systems.
- Expanding transmission enables Quebec hydro to play a greater balancing role in future low carbon power systems in the Northeast. The role of Quebec hydro as a storage resource suggests that building additional transmission is a complement to deploying clean energy in the Northeast, rather than a substitute.

- The Northeast state goals for zero-emission electricity will be achieved at a lower cost if transmission with Quebec is expanded.

c. *Inter-Regional Transmission Expansion*

The current Canadian transmission system is much more focused on international transmission as opposed to interprovincial transmission, and the value of interprovincial transmission expansion has been underrepresented in historical cost-benefit analyses [79].

Expanding interprovincial transmission in Western Canada shows the most benefits in the reliability categories (risk mitigation, resource adequacy, and resilience) compared to the traditional benefit categories (production cost, emissions avoided, capital cost).

The levels of reliability benefits have to be promptly explored/modelled for the inter-provincial and inter-regional connections between Western and Eastern Canada (e.g., Manitoba and Ontario) and between the Eastern and Quebec interconnections (e.g., Ontario and Quebec, and Quebec and New Brunswick), and within Atlantic Canada.

d. *Slower Pace of Regional Integration in Canada*

However, in Canada, contrary to leading regions in the U.S. (such as New York and New England) or in the European Union (such as the Nordic Region [80-82]), integration or harmonization reforms so far have been slow. Understanding of the historic evolution of electricity markets across Canada showed the economic and environmental costs resulting from the poor integration level in the country [83].

To address the slower pace of integration in the North American Northwest, key policymakers and stakeholders in eastern Canada, New York and New England were interviewed in 2020 to determine whether there is sufficient institutional and key stakeholder support in the region for an extended multistakeholder, multi-jurisdictional collaborative process dedicated to developing a comprehensive blueprint for such coordination and grid integration [84].

The results confirmed strong support for a broad-based collaborative effort to promote increased electric grid integration and coordination, and to obtain all the economic and environmental benefits that such integration and coordination is likely to yield. However, the inter-regional collaborative “cannot begin, much less succeed”, unless three “must have” preconditions are met: support of the affected provincial and state governments, access to adequate data to support essential analytical and modeling activities, and sufficient resources to sustain the overall effort.

iv. *Enabling Market Opportunities*

a. *Market Structures Vary*

Electricity market structures in Canada widely vary in vertical integration level, in ownership (from public to private), and in competition level in generation and retail [7]. Having each of the provinces’ regulatory bodies, by mandate, ignore what is going on in other provinces “creates uneven and self-centered provincial electricity markets that are not designed to collaborate and, consequently, are poorly positioned to support an efficient deep decarbonization of the economy”.

Improving integration and coordination of provincially managed electricity systems in Canada opens “key opportunities: economic efficiency gains, the potential to integrate renewable energy, and improved regulation to support innovation” that can be seized through a more integrated electricity sector.

Proposed strategies inducing regional market integration include: “(1) enhancement of bilateral provincial projects through renewed federal support; (2) a bottom-up movement to provincial convergence, following a Nordic approach to collaboration [80-82]; (3) a negotiated free trade agreement in electricity, under the already established Canadian Free Trade Agreement, capitalizing on the existing “Regulatory Reconciliation and Cooperation” process; and finally (4) a federally led, healthcare-type process where key principles would be imposed on provinces to build the more integrated power system of tomorrow” [7].

b. *Benefits and Challenges of Electricity Market Integration*

Generic benefits of regional electricity market integration were shown as follows [85]:

- Improving reliability and pooling reserves;
- Reduced investment in generating capacity;
- Improving load factors and increasing demand diversity;
- Economies of scale in new construction;
- Diversity of generation mix and supply security;
- Economic exchange;
- Environmental dispatch and new plant siting;
- Better coordination of maintenance schedules.

Major regulatory challenges experienced included [86]:

- Possibility to trade interconnection capacity day-ahead and intraday;
- Technical features (e.g. technical losses) properly modelled in the allocation process;
- Gate closure time as close to real time as possible;
- Integration of electricity balancing markets.

Important regional integration obstacles in Canada were recognized as follows [85]:

- Structure of political and electoral incentives in the provinces and the federal government
- Redistribution of the gains from a partial or complete integration
- Lack of recognition of the environmental benefits resulting from integration

c. *Today's Realities of Inter-Regional Trade: RTO vs Regulated Monopoly*

An important reason for slower decision-making on regional and inter-regional power integration in Canada is defined by the critical wholesale electricity market differences in deregulated and regulated monopoly jurisdictions.

Internal market pricing in a deregulated jurisdiction is defined by an RTO-administered wholesale electricity market at marginal cost, and in regulated monopoly jurisdiction - at average cost.

In inter-regional electricity trade the regulated monopoly always exports toward the deregulated jurisdiction pricing at marginal cost which may induce productive inefficiencies of the regulated monopoly. If both jurisdictions are deregulated, "integrated deregulation" in inter-regional electricity trade yields a decrease in overall consumption, which also brings GHG emission reduction [87].

An example of the market differences slowing regional and inter-regional integration is presented by ISO new England with its RTO-administered deregulated market, and New Brunswick and Nova Scotia as regulated monopoly utilities.

d. *RTO Opportunities in Atlantic Canada*

The electricity system will play a key role in achieving greenhouse gas emissions reduction targets of the Atlantic provinces (New Brunswick, Nova Scotia, Prince Edward Island and Newfoundland and Labrador) through decarbonization of energy supply and enabling electrification of buildings and transportation.

Some implications on the electricity system upgrade in the region, with an emphasis on the potential economic benefits of increased regional coordination, include the following aspects [88]:

- In-region renewable electricity generation: the Maritimes will require significant construction of in-region renewable energy to provide zero-carbon energy and decarbonize the electric power supply regardless of regional coordination measures to import dispatchable, clean energy from Newfoundland and Labrador, or/and from Quebec.
- Dispatchability needed for Deep Decarbonization: achieving very deep levels of decarbonization will require firm, dispatchable low-carbon energy and capacity to ensure reliability, which will be possible/ necessary only with broader regional coordination.
- Low carbon dispatchable energy has significant and growing value: "imported hydropower or other dispatchable, clean energy can meet the need for zero-carbon electricity and the need for firm capacity for system reliability, acts as a hedge against significant uncertainty in commercial development of low-carbon baseload and shows significant value under a wide variety of uncertainties, in particular in scenarios examining 2030 coal retirement".

A clear curve of regional collaboration efforts and steps in Atlantic Canada was summarized in the presentation "Regional collaboration and infrastructure optimization in energy modelling" in 2024 [89]. It shows that an RTO in Atlantic Canada has been waited for, is required and much needed. Before looking attentively into deep integration opportunities that may allow Atlantic Canada to promptly and strongly contribute to deep decarbonization of the country, let's review the current situation with and upgrade of electricity wholesale efforts in Canada.

III. Expected Results and Outcomes

a) *Upgrading Electricity Wholesale in Canada*

i. *Alberta and Ontario: Leading Competitive Wholesale*

Canadian power industry paid serious attention to the development and deployment of competitive wholesale electricity markets in the U.S., and followed the rules and achievements established by FERC. The most industrialized provinces of the country – Alberta and Ontario – followed the experiences in the U.S., leading wholesale electricity market deployment in Canada in Western and Eastern interconnections.

a. *Upgrading Operations*

Alberta: Electricity policy in the province changed in 1996, with the province restructuring its electricity market away from traditional regulation to a market-based system [90]. The Alberta Electric System Operator (AESO) started operating in 2003 planning and operating the wholesale market and managing/planning the related power grid [91]. The market now includes an increasingly diverse infrastructure for multiple electricity buyers and sellers. AESO operates "independently of any industry affiliations and owns no transmission or market assets" [92].

Alberta's power system is undergoing the greatest transformation in its history, driven by new technologies, government policy and a societal shift toward cleaner forms of energy, and the AESO is playing a leadership role in enabling this transformation [93].

AESO is a member of the ISO/RTO Council (IRC), Western Electricity Coordinating Council (WECC), Western Power Pool (WPP) and North American Reliability Corporation (NERC).

Ontario: The Independent Electricity System Operator (IESO) was established in April 1999 as the Independent Electricity Market Operator (IMO) under the government of Ontario in preparation for deregulation of the province's electrical supply and transmission system [94]. The IMO was renamed to the IESO in January 2005. It is the Crown corporation responsible for

Global Journal of Research in Engineering (F) XXIV Issue I Version I Year 2024

operating the electricity market and directing the operation of the bulk electrical system in the province.

As a key service across the electricity sector the IESO manages the wholesale market in the province, including planning for the province's future energy needs, and designing a more efficient electricity marketplace to support sector evolution [95]. The IESO identifies system needs and planned actions from 2025 to 2050 that are needed to ensure the reliability, affordability and sustainability of Ontario's electricity system [96]. The IESO is a member of the ISO/RTO Council, NERC and Northeast Power Coordinating Council (NPCC).

b. *Restructuring Energy Markets*

The electricity sector is in a time of fundamental change. Every jurisdiction, regardless of its framework, is experiencing reliability and affordability challenges that are becoming more significant as the pace of change increases [97].

AESO and IESO as the leading Canadian electricity wholesale market operators clearly defined the next steps in addressing these changes through restructuring energy markets.

As Alberta's current electricity system is being impacted by transformational change, the AESO Net-Zero Emissions Pathways Report (Net-Zero Report) [98,99] and the AESO 2023 Reliability Requirements Roadmap (Reliability Roadmap) [100,101] noted key operational and reliability challenges that are having implications on the sustainability of the electricity market as currently designed in Alberta.

The need for more structural change to the market design and provincial electricity policy is being driven, among other emerging trends, by technological shifts changing where and what type of resources power the grid:

- Alberta is experiencing a significant change in its generation fleet with the reduction in carbon-emitting generation sources and the increasing pace of development of variable renewable generation resources (i.e., wind and solar). The integration of these resources is important to support a carbon-neutral future. However, these resources must be operated with an accompanying mix of controllable resources.
- Increasingly, supply is not providing attributes that are required to maintain reliability without the need for additional ancillary services and/or technical requirements.

AESO's approach to restructuring energy markets to address this change including the AESO's study, observations and recommendations was presented to the Alberta government in January 2024 [102].

A key recommendation of AESO addresses the ability to procure contracts for controllable/dispatchable technologies[1] focused on the objectives of Reliability, Affordability, Decarbonization by 2050, and Reasonable Implementation. A set of different dispatchable technologies supporting these objectives and demonstrating the current and future role and potential, in AESO's opinion, includes carbon-abated natural gas power, full-scale nuclear, small modular reactors, hydrogen-fueled generation, hydroelectric power, and energy storage resources. Specifically, the reliability objective involves defining and establishing sound technical requirements for all technologies, especially a new and growing class of inverter-based resources (e.g., wind turbines, solar arrays, and batteries).

While AESO worked promptly in 2024 on the Restructured Energy Market design development and engagement (see [103, 104]), IESO also completed its Market Renewal Program [105]. The mission of the Market Renewal Program is to deliver a more efficient, stable marketplace with competitive and transparent mechanisms that meet system and participant needs at lowest cost. The Market Renewal Program (MRP) is modernizing Ontario's electricity markets to address inefficiencies and will be a building block to embrace the continued transition to new and diverse resources [106]. MRP will make improvements to the current electricity market design, by improving how electricity is supplied, scheduled and priced by IESO, leading to system efficiencies and supporting the grid of the future. This project will deliver significant value to the system and Ontario consumers – an expected $700 million in benefits in the first 10 years alone.

c. *Accommodating DER Aggregations*

In parallel and in coordination with restructuring their energy markets, IESO and AESO have been collaborating with their stakeholders to understand the ways to accommodate DER aggregations (DERA) in their markets.

In response to FERC's Order 2222 [107], ISO/RTO across the US are developing and implementing wholesale participation models for DERs that inform potential enhancements in IEASO and AESO. This includes:

- Opportunities to enable new and more diverse DER aggregations (DERAs) to better reflect existing and emerging DER potential in the province
- Potential to enable greater flexibility of aggregated demand-side resources
- Addressing barriers to participation for small resources (e.g., metering/telemetry processes and requirements)

The key areas include DERA participation (e.g., participation and aggregation models will be established

[1] When referring to different types of supply, the terms dispatchable and controllable are used by AESO interchangeably to represent technologies that can be dispatched and controlled in real time.

for DERs, maximum and minimum size thresholds needed for individual DERs and/or DERAs, etc.), eligible wholesale market services (e.g., energy, operating reserves and capacity) and metering and settlement for DERAs [108].

IESO sees DERs as emerging major players in the electricity sector in Ontario with at least 5000 MW* of DERs that IESO has visibility to as a result of markets, procurements, programs and initiatives have already been deployed in Ontario. IESO sees potential for substantial growth [109] with additional DERs being deployed to support customer and policy-driven electrification and decarbonization goals, and has been determining cost-effective ways to enhance the value DERs can provide to Ontario's electricity system by expanding participation in the wholesale markets.

As an example, the IESO's Market Vision and Design Project [110] as a key focus area of DER integration activities explored with stakeholders "foundational" participation models for DER integration into wholesale markets as well as enhanced models to form future DER integration [111]. IESO also plans by 2026 to design in detail and implement the foundational wholesale participation models including market rule/ manual amendments and process/tool updates [112].

Table 4.1: Key Features of Foundational and Enhanced Models [112]

Key Features of Foundational and Enhanced Models

Key Focus Area	Foundational Model	Enhanced Model
Aggregation Details	• Enables aggregation at a single node • Enables heterogeneous aggregation of certain resource types • Aggregation of residential and small C&I consumers not enabled	• Enables sub-zonal (or multi-nodal) aggregation • Enables heterogeneous aggregation of all resources except very small consumers which must be aggregated with resources similarly dependant on Smart Meters • Aggregation of residential and small C&I consumers is enabled
Size	• Enables DER Aggregations (DER(A)) with a total size of 1 MW or more and will explore the possibility of reducing the threshold for the aggregation size; no minimum size for individual contributors	• Enables DER(A) of 100 kW or more; no minimum size for individual contributors to an aggregation
Products and Services	• Capacity, Energy and Operating Reserve	• Capacity, Energy, Operating Reserve and, if there is a system need, regulation service
Metering and Settlement	• Applies existing, relaxed IESO requirements for small resources to DER(A)	• Will allow for alternative requirements for residential/small C&I DER(A) (by utilizing the Smart Meter Entity for settlement purposes) that reflect the size of the resources and risk mitigation capabilities of participating in aggregate

6

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Another example is collaboration of AESO with its stakeholders on the development of proposed Amendments to ISO rules related to the Operating Reserve ("OR") Market Review ("OR Market Review Rule Amendments") related to DER/DERA. By May 31, 2023, AESO received comments from its Stakeholders in response to its March 29, 2023 Letter of Notice for Development of Operating Reserves Market Review Rule Amendments [113], and by July 31, 2023 provided its feedback to the stakeholders.

ii. *British Columbia: Moving to Deep Integration*

BC Hydro, a Crown Corporation of the province of British Columbia, participates in wholesale energy market activities in the Western Interconnection of North America via Powerex Corp., a wholly-owned subsidiary of BC Hydro [114]. The surplus capabilities of the BC Hydro generating system and Powerex's portfolio of transmission service rights enable Powerex to buy, sell and shape power deliveries to BC Hydro customers across the Western Electric Coordinating Council (WECC) region.

Powerex began its participation in the real-time Energy Imbalance Market (EIM) administered by California Independent System Operator (CAISO) on April 4, 2018, pursuant to Commission-approved agreements that recognize its status as a Canadian EIM entity [115]. Powerex has been participating in the EIM in the same format as many other EIM entities in the market managed by CAISO. This includes [116]:

- Flexible Generation - voluntary bids and offers from residual BC Hydro flexible generation;
- Generation and Load Imbalances - deviations from hourly base schedules;
- Transmission rights - set aside ahead of the hour to support EIM transfers.

In November 2022 after its careful review of the two competing alternatives for a fully-integrated RTO solution demonstrating deep integration in the Western interconnection: SPP's Markets+ and CAISO's Energy Day Ahead Market/Energy Imbalance Market (EDAM/ EIM), Powerex concluded that SPP's Markets+ is the market platform that will provide Powerex with the greatest economic, environmental and reliability benefits [117, 118]. Powerex announced that "it will not only participate in the funding of the development of Markets+, but it will also join Markets+ at inception, subject to applicable approval processes".

The following elements of the Markets+ Draft Service Offering were "particularly important to Powerex's decision to pursue Markets+:

- A durable and inclusive governance framework that is in palace from the outset, supported by an experienced and neutral market operator, and the independence of a Markets+ Independent Panel and the SPP Independent Board;
- An approach to GHG tracking that is expected to accurately apply GHG emissions costs to energy generated in, or imported into, jurisdictions with GFHG pricing programs, and in a manner that meets the full intent and spirit of the underlying environmental policy;
- A common resource adequacy requirement that will not only protect reliability, but do so in an equitable manner, leveraging the Western Resource Adequacy Program (WRAP);
- A transmission proposal that will maximize the transmission capability available to Markets+ while minimizing impacts on third-party transmission revenue and equitably allocating congestion revenue to OATT customers, and
- Application of industry best practices in price formation, consistent with FERC policy, ensuring that market prices accurately reflect grid conditions, which drives lower retail rates for consumers over the long-term while supporting reliability".

On Mar 25, 2024, SPP's Board of Directors and its members have approved the initial tariff for its Markets+ service offering in the Western Inter-connection, clearing the way for its filing at FERC [119]. As of April 2, 2024, Markets+ is expected to go live in early 2027, pending FERC approval of the tariff [120].

iii. *Manitoba and Saskatchewan: Building RTO Alliances*

Both Manitoba Hydro and SaskPower made important steps toward strengthening wholesale markets in North America via alliances with leading RTOs in the U.S.

Saskatchewan: In 2022, SaskPower signed a 20-year agreement starting in 2027 with the Southwest Power Pool (SPP) increasing its ability to sell and buy bulk power at the wholesale power market for the central United States managed by SPP [121]. SaskPower is SPP's first international member, and their membership represents both organizations' continued efforts to increase reliability through interregional coordination [122]. SPP and SaskPower have operated as adjacent entities since October 2015 when SPP's service territory expanded to the North Dakota-Saskatchewan border, coordinating their reliability and transmission functions. SaskPower's participation in the SPP represents a commitment by both organizations to strengthen wholesale market opportunities across their borders.

Manitoba: Manitoba Hydro joined MISO in September 2001 through the execution of a Coordination Agreement [123]. With an installed capacity of close to 5700 MW of hydro power generation Manitoba Hydro operated as a strong contributor to clean electricity resources supplying its U.S. customers with power and energy via the wholesale market managed by MISO. In addition to participating in MISO as the Coordinating Owner, Manitoba Hydro also participates in the MISO Capacity, Ancillary Services, Energy and Financial Transmission Rights markets through which it delivers to the MISO footprint approximately 1000 MW of capacity and 10 TWh of energy on an annual basis.

iv. *Quebec Selling to Wholesale Markets in Northeast*

a. *One Utility, One Interconnection*

Hydro-Québec is a vertically integrated provincially-owned power utility established by the government of Quebec. Hydro-Québec's electricity transmission system is managed by its division - Hydro-Québec TransÉnergie (HQT). Quebec Interconnection covering the province of Quebec and operated by HQT is not synchronized with Eastern Interconnection or any other interconnections in North America [124]. TransÉnergie uses HVDC technology (back-to-back converters) to export or import electricity to other transmission grids in the neighbouring Eastern Interconnection.

HQ and the Quebec government have been working successfully (and not without hardships) to increase electricity exports to the U.S. via existing and proposed new transmission lines [125]. Major electricity supply provided by HQT to ISO/RTO wholesale markets in North America includes IESO (Ontario), ISO NE (New England) and NYISO (New York). Today, with the American Northeast committed to rapidly scale variable renewables, inter-regional collaboration between Quebec and the Northeastern U.S. is underway that may "fundamentally reconsider the role of hydropower on the grid" [126, 127].

Inter-regional efforts and opportunities for Quebec are proposed by leading universities in Quebec and well documented, e.g., [6-8, 83, 85, 87, 128-132].

b. *The "Battery" of Northeastern America*

According to Quebec's Framework Policy on Electrification and the Fight Against Climate Change [133, 134], "the provincial government is aiming to use our considerable hydroelectric resources to make Québec the "battery" of northeastern America. This involves the ability to use electricity exports to contribute to the fight against climate change beyond Québec's borders and the potential to attract even more

Global Journal of Research in Engineering (F) XXIV Issue I Version I Year 2024

companies that want to take advantage of this clean, competitive energy".

"By 2030, the government has set its sights on increasing electricity exports to neighbouring markets under long-term contracts. It will propose energy alliances to neighbouring provinces and states in the American Northeast in order to promote Québec's resources and increase electricity exports. These energy alliances will make the American Northeast a greener, more competitive region."

According to Hydro Quebec Action Plan 2035 [135], the utility plans to integrate 8,000 to 9,000 MW of new generation assets into the Hydro-Québec grid. As hydropower is the best option for firming up intermittent wind power In Québec, from 3,800 to 4,200 MW of new hydropower will be added by increasing the capacity of the existing generating stations and building new hydropower facilities, including a pumped-storage facility.

Transmission infrastructure will be deployed to connect additional generating facilities and promising new projects for Québec. By 2035, Hydro-Québec plans to invest a total of $50 billion to install 5,000 kilometers of transmission lines to increase the capacity of our transmission system in order to maximize access to new generation. About half of which will be high voltage (735 kilovolts and 315 kilovolts) and the other half intermediate voltage (between 69 kilovolts and 315 kilovolts) for regional development and local loads [136]. Hydro-Québec plans to launch a major undertaking to upgrade 735-kV lines: the backbone of Québec's transmission system. The first phase will include the optimization of the existing system and the construction of almost 850km of new 735-kV or 315-kV lines, as well as 5 strategic new substations in 3 areas. This infrastructure will allow new generation to be integrated into the grid, transmit additional energy across Québec and increase grid reliability and resilience to increasingly intense weather phenomena [137, 138].

As the Reliability Coordinator for the Quebec's electricity system, Hydro-Québec on October 1, 2024 updated all the data and information it needs to monitor the transmission system of Québec and meet its operational obligations, including to perform Operational Planning Analyses, Real-time monitoring, and Real-time Assessments, as Reliability Coordinator (RC), Balancing Authority (BA) and Transmission Operator (TOP), under the established by NERC reliability standards [139].

c. *Amping Up Electricity Regulation*

On June 6, 2024 the Government of Québec tabled Bill 69, An Act to ensure the responsible governance of energy resources and to amend various legislative provisions, in the National Assembly [140]. The bill is essentially aimed at speeding up green energy production in the province, with the ambition of making Québec the first carbon-neutral jurisdiction in North America. Although electricity appears to be at the centre of Bill 69, some changes are also aimed at natural gas and other sectors of the energy supply chain of Québec. According to current strategies and plans, Quebec needs to double its energy production to support initiatives that will allow it to reach its climate targets [141].

Specifically, Bill 69's proposed amendments would [142]:

- Enable Hydro-Québec to enter into renewable electric power supply contracts without being subject to tendering obligations, as well as give Hydro-Québec the ability to sell certain production infrastructure;
- Allow private producers to sell and distribute electric power to other private entities located on a site adjacent to their production site; and
- Introduce a new governance model.

Bill 69, which aims to set up a legal framework to support the province's energy transition [143], is expected to be adopted by the end of 2024.

Keeping in mind the current wholesale electricity updates in all the provinces in Western Canada, Ontario and Quebec, the regional wholesale market reasons and solutions for Atlantic Canada contributing to deep decarbonization via Canada's Clean Grid are proposed in the following chapter.

b) *Atlantic RTO as the Energy Gateway Solution*

i. *Atlantic Energy Gateway*

In March 2009 Atlantic Canada made a next step in expanding regional clean electricity collaboration announcing the Atlantic Energy Gateway (AEG) to enhance the development of Atlantic Canada's clean energy resources. AEG represented a collaborative approach coordinated by the Federal Government (Natural Resources Canada and the Atlantic Canada Opportunities Agency), with participation from the governments of the four Atlantic Provinces, four of the major regional utilities, and the Region's two system operators [26, 27].

With emerging clean electricity opportunities in the region ranging from large hydro to wind and tidal power in clean electricity generation and green hydrogen production in clean consumption, the Atlantic Energy Gateway was seen as one of the strategic gateways to prosperity in Atlantic Canada and beyond [28-31].

In early 2011 energy ministers of the Atlantic provinces agreed to speed up regional co-operation efforts, identify priority opportunities and maximize benefits for the region [144]. By March 2012 strong advances were made in better understanding of the ways to move in regional clean electricity collaboration.

On September 10, 2012, the federal and provincial ministers announced the results of studies undertaken under the AEG. The research identified significant potential benefits of regional collaboration, including development and operating cost efficiencies, greater diversity in clean energy supplies, enhanced stability for ratepayers and lower greenhouse gas emissions in the Atlantic region. The research involved significant engagement of the power utilities in the four Atlantic provinces [27].

Specifically, the following understanding below was shared and agreed upon within the AEG initiative.

a. *Market Opportunities*

The AEG team completed a review of provincial and state clean and renewable energy policies supporting clean and renewable energy targets [145]. The review highlighted that the Atlantic provinces will only cooperate, and truly "buy-in", if there is mutual gain. Greater interprovincial power cooperation was seen necessary for a successful export to New England.

The review highlighted a need for a Regional System Operator that could provide coordinated balancing and load following services for the region. A regional system operator could provide a more efficient and economic structure to facilitate interprovincial power flows. In addition to streamlining the tariff system, a regional system operator that had independence from individual provinces' political decision-making could improve market access for independent producers.

b. *Regional Electricity System Operations*

The AEG initiative's review of Regional Electricity System Operations in Atlantic Canada was focused on the operations and requirements of a regional transmission system [26]. The review also included a description of the regulatory systems in place in the Atlantic Provinces, and also other relevant regulators including the U.S. Federal Energy Regulatory Commission (FERC), North American Electric Reliability Corporation (NERC), Northeast Power Coordinating Council (NPCC) and Canada's National Energy Board (NEB), regulating international power lines, and energy imports and exports in Canada.

It was indicated that "increasing regional electricity and clean renewable energy cooperation could achieve potential efficiencies and cost benefits to consumers and industry, and expand economic opportunities and benefits for the region. Implementation considerations and some areas that could be reviewed in exploring increased coordination are:

i. Existing generation and transmission structures and policies;
ii. Examining opportunities for regional planning for expanded renewable energy
iii. Sources to maximise market competitiveness;
iv. Planning for future system operations on a regional basis; and
v. Harmonizing certain regulatory functions, while ensuring the Atlantic region maintains its close regulatory, reliability, and business relationships with the Northeast USA and related agencies.

Increasing cooperation and coordination by the Atlantic Provinces' electricity sectors could become the start of an Atlantic Canada power market that is more competitive, both locally and internationally."

c. *Regional Transmission Upgrade Options*

As a tighter integration of the regional Atlantic Canada electrical system was expected to lead to increased opportunities for inter-provincial energy trade, a resource assessment of the integrated regional system was done through the development of a representative model of the system [146]. The model was used to evaluate the current operation of the system and develop scenarios for increasing amounts of renewable and non-emitting energy sources for domestic and export electricity uses. Various potentially desirable transmission upgrade options and the key interfaces between New Brunswick and Nova Scotia, and New Brunswick and Prince Edward Island were identified to determine their approximate transfer capabilities and the costs to upgrade transmission facilities.

d. *Common Unit Commitment and Dispatch Functionality*

The AEG initiative supported the development and testing of a regional system model, database, and skill set a common unit commitment and dispatch function for balancing electricity supply and demand in Atlantic Canada to be used for future studies [147]. This was a model upgrade from the New Brunswick System Operator balancing at that time New Brunswick, Northern Maine and Prince Edward Island systems as one balancing area. The results of the common unit commitment and dispatch functionality review were intended to inform policy makers on the appropriateness of pursuing a common system balancing function.

e. *Clean Electricity Resources*

The AEG Resource Development Modeling Study was focused on regional integrated resource planning (IRP) of future electric generating resources rather than IRP done separately by each of the Atlantic utilities for their medium and long term future generation development for the period of 2015 through 2040 [148]. The objective of the study was to model a more integrated view of the region and determine the economic and environmental benefits compared to the individual provincial models.

f. *Renewable Generation Supply Chain Opportunities in Atlantic Canada*

The Atlantic Energy Gateway initiative examined a range of issues associated with opportunities for Atlantic Canadian firms in the supply chain for various renewable generation technologies, including onshore wind, offshore wind, tidal energy, biomass energy, and systems to power remote on- and off-grid communities [149].

A summary of Renewable Generation Supply Chain Opportunities included the following (see excerpts from [149] below:

- The supply chain for onshore wind is currently robust, but still offers a number of service-related opportunities to Atlantic Canada, including crane services for installations, operations and maintenance, and logistics services.
- Supply chain development for offshore wind and tidal power, had been limited in the region due to the nascent state of these technologies. However, should these technologies reach commercialization, the resulting supply chains, which have much in common, will offer significant opportunities to the economies of Atlantic Canada as Atlantic Canada is well positioned in both geography and industrial infrastructure to contribute substantially to these supply chains as they mature.
- A healthy biomass supply chain is already established in Atlantic Canada, but opportunity exists to expand this supply chain. Thermal energy applications, especially exports, present the greatest opportunity for growth, but electric generation appears to offer less potential.
- Potential supply chain opportunities also exist related to the development of systems to power on- and off-grid applications that displace diesel generation with renewable resources. Local firms involved in wind/hydrogen demonstration projects may benefit from forming partnerships to develop a standardized control system that would allow for turnkey replication of these wind/hydrogen facilities. The off-grid use of biomass for district heating and/or cogeneration was also analyzed and may offer further supply chain opportunities through greater application in district heating and remote communities.

g. *Research, Development and Demonstration*

The AEG initiative reviewed a complete picture of the clean and renewable energy RD&D activities in Atlantic Canada, both in terms of types of technologies being pursued, and the intellectual and institutional resources present in the region, to help direct future strategies [150]. The AEG RD&D review presented summaries of the current state of clean and renewable energy used in each of the four Atlantic Provinces, and of their research and development capacity. Potential areas of regional cooperation were presented, along with policy considerations intended to support the AEG's clean and renewable energy development initiatives.

ii. *Looking into a Clean Electricity Future in Atlantic Canada*

a. *Leveraging the Pan-Canadian Framework on Clean Growth and Climate Change*

The next step in enhancing clean energy opportunities in the Atlantic region was made by the Pan-Canadian Framework on Clean Growth and Climate Change (PCF), a collective plan to grow the economy while reducing emissions and adapt to a changing climate [151]. In December 2016, the PCF, published the outline of a collaborative action plan to meet or exceed Canada's 2030 target of a 30 percent reduction below 2005 levels of greenhouse gas (GHG) emissions. Specific actions to transform regional electricity systems supported by PCF included: (1) increasing the amount of electricity generated from renewable and low-emitting sources; (2) connecting clean power with places that need it; (3) modernizing electricity systems; and (4) reducing reliance on diesel working with Indigenous Peoples and northern and remote communities.

Within PCF the federal government committed to investing in infrastructure through a number of national programs, negotiated agreements with provinces and through the Canada Infrastructure Bank, a federal Crown corporation using federal support to attract private sector and institutional investment to new revenue generating infrastructure projects that are in the public interest. Specifically, the Green Infrastructure stream, through Integrated Bilateral Agreements (IBA), allocated investments in the Atlantic provinces with a minimum of 45% of a province's IBA Green Infrastructure stream allocation supporting greenhouse gas emission mitigation projects, such as new renewable electricity and transmission projects.

To update a regional infrastructure perspective, a regional study was conducted to identify promising electricity infrastructure projects in Atlantic Canada. Specifically, the governments, and their respective electric utilities, of Nova Scotia, New Brunswick, Prince Edward Island, Newfoundland & Labrador and the Atlantic Canada Opportunities Agency collaborated on a regional economic dispatch simulation model to examine promising electricity infrastructure projects to meet a set of carbon-constrained future scenarios.

The regional power grid infrastructure was looked at in terms of current and future diverse clean energy supply led by large hydro and nuclear.

Major hydro advances included the Newfoundland and Labrador Muskrat Falls Project, including its associated transmission projects, to make Newfoundland and Labrador's electricity generation 98% renewable and provide Nova Scotia with 20 percent of the energy and capacity from the Muskrat Falls 824 MW generating station.

Considerations were given to electricity from Churchill Falls, a 5,428 MW hydro generating station operated in Labrador, that will be available for the Atlantic regional trade operations after a long-term power purchase agreement (PPA) with Hydro-Quebec expires August 31, 2041. The Government of Newfoundland and Labrador also saw the 2,250 MW Gull Island renewable energy project on the lower Churchill River as a potential future development opportunity.

In terms of nuclear, New Brunswick Power explored the possible use of Small Modular Reactors at the existing Point Lepreau Nuclear, a 660 MW Generating Station.

Modelling potential futures for the regional electric system showed that regional electricity transmission reinforcement is required enable the introduction of more sources of renewable energy, and that developing new non-emitting "dispatchable" resources is needed to provide firm capacity. It was confirmed that coordinated regional action can achieve deep GHG emissions reductions required. At that time, decision was made to further explore the Regional Hybrid Portfolio Scenario to identify optimal incremental changes to the regional system [88]. This includes investigating an appropriate amount of dispatchable firm generation capacity, and/or storage and demand-side management systems, and transmission reinforcement to support more sources of variable renewable generation for further GHG reduction.

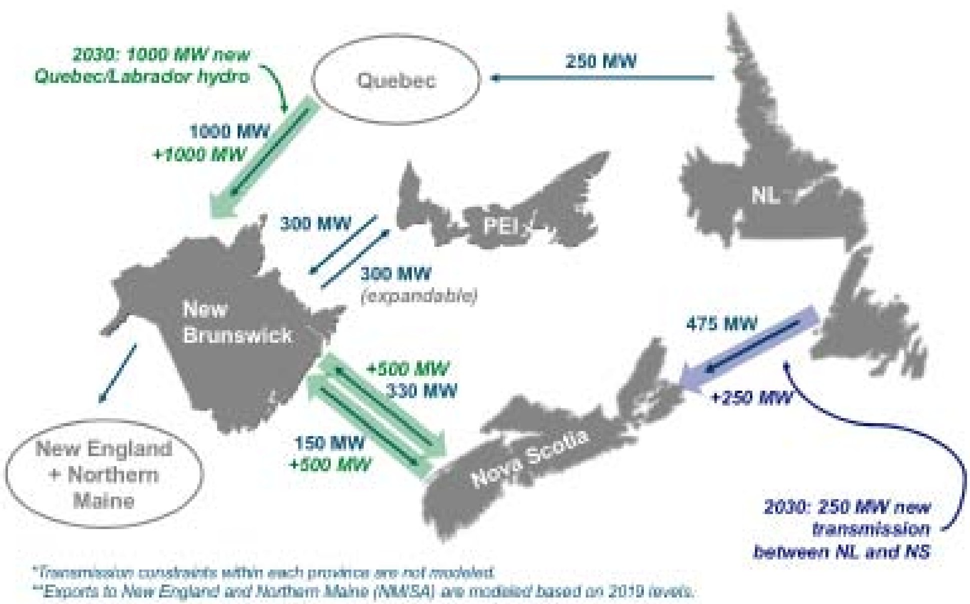

Fig. 5.1: Regional coordination scenarios: electric load zones and transmission capacities [88]

b. *Advancing a Clean Power Roadmap for Atlantic Canada*

Building on a long history of collaboration, in March 2019, the Atlantic Provinces and the federal government agreed to develop a Clean Power Roadmap for Atlantic Canada. The Roadmap was intended to outline a collective vision for how the Atlantic provinces may collaborate over the coming decades to build a clean power superhighway across the region [32].

Specifically, a shared vision of an interconnected clean power grid was agreed to serve as the foundation for a competitive, electrified economy across the region. "The integrated grid would provide Atlantic Canadians with an affordable and reliable supply of clean power, underpinned by a regionally integrated, modern electricity system that better optimizes supply and demand through smart grid technology and energy storage. It could lead to more efficient investment and management of costs; more choices and economies of scale in building new sites; better coordination of system maintenance, and increased reliability" [32].

The transition planned for Atlantic Canada's power system was seen as significant, opening "new, untapped environmental and economic potential" [33].

A strengthened Atlantic Regional Transmission Loop approach was proposed as the backbone of the regional grid that would connect existing and new power supplies across the region to places that need it, along with smarter distribution networks that optimize supply and demand while maintaining reliability.

The initial Atlantic Loop concept was modified in October 2023 [152] with a focus on expanding "Clean, Reliable and Affordable Electricity Grids in New Brunswick and Nova Scotia" [153, 154]. As part of the first track of collaborative work, priority projects required to meet the 2030 timeline included the building of the Salisbury-Onslow Reliability Tie connecting Nova Scotia and New Brunswick. Under the second track of work, the parties agreed to confirm and advance areas of critical importance and cooperation on the path to net-zero electricity by 2035, including the continued advancement of Small Modular Reactors, which is specific in New Brunswick, and offshore wind, which is specific in Nova Scotia. This also included further exploring regional transmission and energy exchange opportunities in partnership with neighboring utilities, in Quebec, Newfoundland and Labrador, and Prince Edward Island.

According to Nova Scotia's 2030 Clean Power Plan [155], "NS-NB Regional Transmission Nova Scotia's electricity system is only weakly connected to the North American grid, through New Brunswick. A new 345kV line to NB is needed to manage renewables, boost reliability and resiliency. This NS-NB Reliability Tie will run from Onslow to Salisbury, enabling 500MW+ of imports/exports. This project is expected to be online in 2028. Extending this line to Point Lepreau would enable greater access to NB, New England, and Quebec. This new line and extension can be completed by 2029 at a total cost of ~$1.4B, far less than the Atlantic Loop. This supports regional population growth; enhances reliability; and enables more energy trading. Interprovincial & Federal talks are underway to support these transmission investments."

c. *Atlantic Canada's Economy: Commitments and Opportunities*

Atlantic governments and businesses have been significantly investing in the development of clean technologies to support the net-zero transition:

Clean Generation:

- *Muskrat Falls Hydro:* The Muskrat Falls Hydroelectric Project includes the hydroelectric generating facility on the lower Churchill River in Labrador, transmission infrastructure linking the facility to the Churchill Falls facility upstream, and the Labrador-Island Link (LIL) transmission line. Construction of the 824 MW Muskrat Falls facility began in 2013 and was commissioned in November 2021 [156]. The Labrador-Island Link was commissioned in April 2023 [157]. The station at Muskrat Falls has a capacity of over 824 MW and provides 4.5 TWh of electricity per year. [158, 159]

  The Muskrat Falls Hydroelectric Project provides an opportunity to consider Phase Two of the Lower Churchill Project that would consist of the development of the 2,250 MW Gull Island generation facility and associated transmission to markets.

Advanced Transmission

- *Completion of HVDC Power Transmission Lines*

Labrador - Island Link (LIL) is a 1,100 km 900-megawatt (MW) high voltage direct current (HVDC) transmission line that carries electricity from a generating facility at Muskrat Falls to the island of Newfoundland [160].

Maritime Link involves a 500 MW (+/- 200 kV) high-voltage direct current (HVDC) transmission line, as well as a 230 kV HVAC (high-voltage alternating current) transmission line [161] that carry electricity from Newfoundland to Cape Breton, Nova Scotia. Maritime Link was commissioned in 2017 [162].

- *Deployment of Utility-Scale Battery Storage*

Demonstration of Atlantic Canada's leadership in growing utility-scale battery storage [163] includes:

Saint John Energy, New Brunswick: A utility-scale battery energy storage system used as a part of the 42 MW Burchill Wind Project in Saint John, New Brunswick.

The battery is the largest in New Brunswick. It consists of a 5.8 megawatt/11.6 megawatt-hour lithium-ion battery that can deliver 5.8 megawatts of energy to the Saint John Energy grid for a two-hour period on a full charge [164].

NB Power, New Brunswick: Procurement for 50 MW of new battery energy storage in 2023 [165].

Nova Scotia Power: Funding has been committed under the Smart Renewables and Electrification Pathways Program to Nova Scotia Power for three grid locations at White Rock, Bridge Water and Spider Lake, Nova Scotia to install and integrate battery energy storage and grid modernization assets and operating systems totalling 150 MW, 600 MWh in these locations. The Nova Scotia Utility and Review Board approval of three 50-megawatt four-hour duration lithium ion batteries in June 2024. The batteries are supposed to be operational by 2026 [166]. According to Nova Scotia Power Inc., these projects are expected to provide the required firm capacity, renewable integration, frequency and voltage support, and reliability services, to support the transition off coal and continue greening the Nova Scotia electricity system while maintaining a healthy and resilient grid. The utility sees utility-scale battery storage as "poised to play a key role in Nova Scotia's energy transition."

Expectation of clean electricity/clean grid opportunities in the region, according to [167], means that:

- "Future economic opportunities associated with clean technologies will depend on the direction of government regulation, resource availability and investment costs.
- Onshore wind investment is expected to grow strongly over the next decade. Economic opportunities are limited as most major wind farm components are imported.
- Offshore wind projects could create larger local benefits, compared to onshore wind projects, as a much bigger share of the work can be completed

locally. Efforts are underway to adapt the current regulatory environment to accommodate the management of offshore wind projects.

- New hydroelectricity projects in our region are largely limited to Newfoundland and Labrador. These projects would generate large economic benefits if they move forward, but challenges remain to lessen risks around costs and regional integration.

The following clean energy developments are currently considered in the region:

Clean Generation

Offshore Wind Generation in Nova Scotia and Newfoundland and Labrador: The federal-provincial Clean Power Roadmap for Atlantic Canada has already recognized the opportunities for both onshore and offshore wind power [168], and Nova Scotia's provincial government has set a target to license 5 GW of offshore generation capacity by 2030 [169]. It is considered that offshore wind for Atlantic Canada could be "what oil was to Texas or hydro power to Quebec" [170].

In April 2022 the governments of Canada, Newfoundland and Labrador and Nova Scotia committed to expand the mandates of the Offshore Boards in Newfoundland and Labrador and in Nova Scotia to include the regulation of offshore renewable energy development, such as offshore wind [171]. An Act to amend the Canada—Newfoundland and Labrador Atlantic Accord Implementation Act and the Canada-Nova Scotia Offshore Petroleum Resources Accord Implementation Act and to make consequential amendments to other Acts (Bill C-49 [172]) passed third reading in the House of Commons in May 2024 and in the Senate on October 1, 2024, and received royal assent on October 3, 2024. This legislation enables the development of the offshore wind industry in the region.

The Draft Regional Assessment Report for Offshore Wind Development in Nova Scotia was presented to Indigenous Peoples and the public for review and comments on October 31, 2024 [198-200].

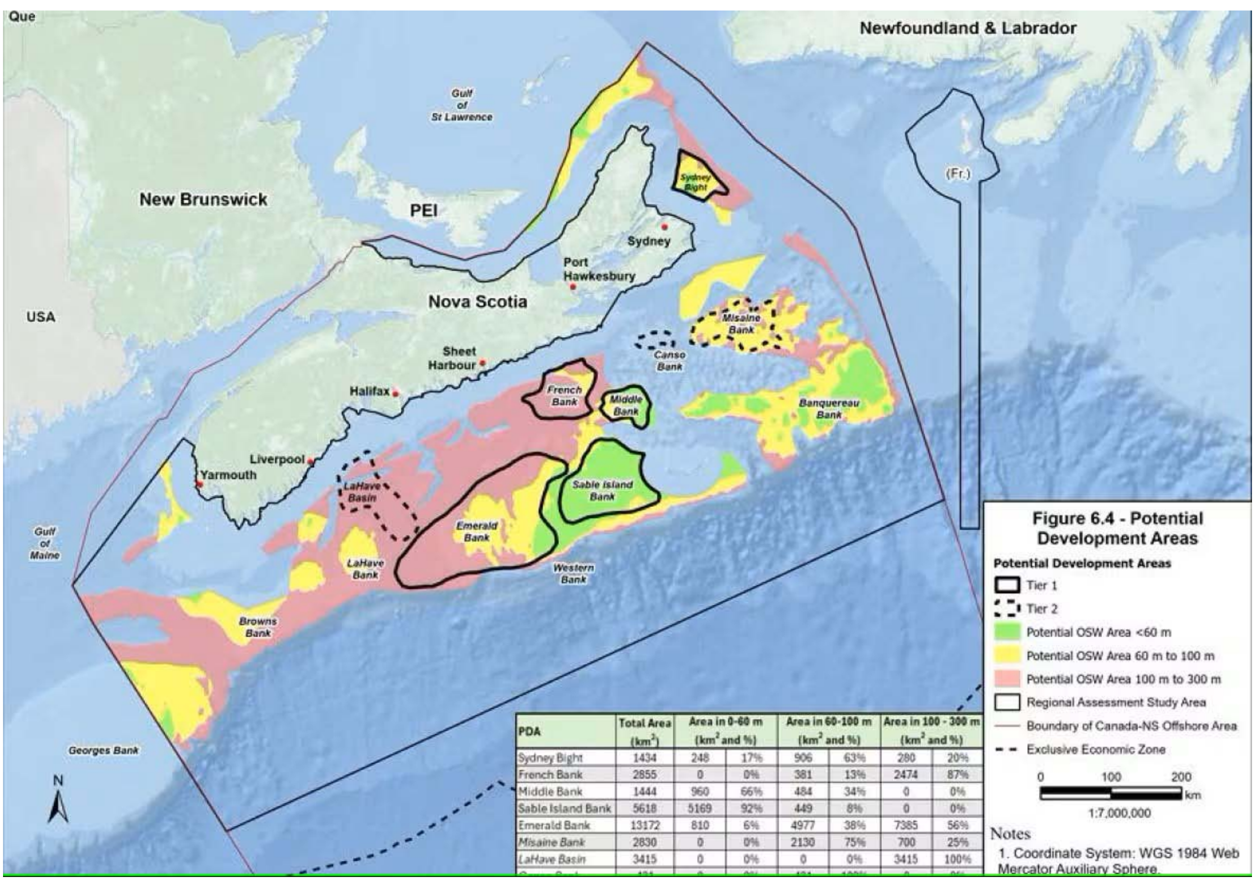

Fig. 5.2: A map of potential development areas for offshore wind on the Scotian Shelf [200]

Advanced Transmission

According to Nova Scotia Regional Energy and Resource Table Framework for Collaboration on the Path to Net-Zero [173], as of August 29, 2024, focused collaboration in the short-term included the following vision:

- Work planned to advance the Point Lepreau–Salisbury-Onslow Transmission Line as part of a modified Atlantic Loop connecting Nova Scotia and

New Brunswick, with a target in-service date of 2029.

- Explore regional transmission and energy exchange opportunities in partnership with utilities in New Brunswick, Quebec, Newfoundland and Labrador, and Prince Edward Island.

As well, socio-economic studies of a New England - Maritimes Offshore Energy Corridor [174] are being considered. This Corridor presents a new HVDC transmission intertie between Nova Scotia and New England to connect two distinct offshore wind resource areas with the two load centers in each respective region, highlighting the economic and environmental benefits.

Consumption

Green Hydrogen and Clean Ammonia Production in Nova Scotia: Nova Scotia is actively pursuing the development of a green hydrogen sector, positioning itself as a leader in clean economic growth and environmental stewardship [175].

In alignment with its environmental and climate change goals, the Province is exploring the vast potential of offshore wind energy to produce green hydrogen and its derivatives such as green ammonia.

Nova Scotia is being engaged in ongoing discussions with Natural Resources Canada regarding Nova Scotia's role in meeting Canada's export ambitions under the Canada-Germany Hydrogen Alliance [176-178]. The province is also reviewing the environmental assessments for the EverWind Point Tupper Green Hydrogen/Ammonia Project – Phase 1 [179] and the Bear Head Energy Green Hydrogen and Ammonia Production, Storage and Loading Facility projects [180]. The approval of each project is contingent on each proponent fulfilling a series of terms and conditions to ensure the environment and human health remain protected.

d. *Nova Scotia's Energy Reform 2024*

New legislation introduced on February 27, 2024, allowed for modernizing Nova Scotia's electricity system and enhancing public utility regulation in the energy sector [38, 39]. Supporting continuing strong efforts of Nova Scotia's government to ensure provincial ratepayers have clean, reliable and affordable electricity, the new legislation is changing the way the electricity system in Nova Scotia is structured and regulated, making it more accountable, transparent and competitive. Nova Scotia's government refers to a similar approach to managing and regulating the electricity system in other Canadian provinces [39]. The legislation reflects most significant recommendations of the Clean Electricity Solutions Task Force report of January 31, 2024 [181].

According to a legislation summary, The Energy Reform (2024) Act (the "ERA") includes the following [182]:

1. The ERA creates two new statutes: *More Access to Energy Act* ("MAEA") and *Energy and Regulatory Boards Act* ("ERBA"). The ERA also repeals the *Utility and Review Board Act* and amends the *Public Utilities Act*, *Electricity Act* and other legislation.
2. The MAEA will create an independent energy system operator ("IESO"), which will be responsible for the electricity grid system operator functions, including oversight of wholesale market rules, interconnections, system planning and procurement. The IESO is to be a non-profit corporation, with management and control being vested in a Board of Directors initially appointed by the Governor in Council, and later in accordance with its by-laws. The Nova Scotia Department of Natural Resources and Renewables expects the IESO to be fully operational by late 2025.

The MAEA provides that the IESO is to pursue the following objects:

- Enter into agreements with transmitters giving the IESO the authority to direct the operations of their transmission systems;
- Direct the operation of the IESO-controlled grid;
- Establish and enforce criteria and standards relating to the reliability of the integrated electricity system;
- Maintain the adequacy and reliability of the bulk electricity system;
- Enter into interconnection agreements with transmitters; and
- Facilitate the operation of a competitive electricity market.

In support of the above-noted objects, the IESO is to perform the following functions:

- Carry out competitive procurements, including for electricity supply, capacity, energy storage, ancillary services and "hybrid peaking resources", or as prescribed by regulation or considered appropriate in accordance with the Province's 2030 Clean Power Plan;
- Issue administrative penalties in accordance with market rules and procedures; and
- Carry out transmission interconnection studies.

Under the MAEA, a license will be required to own or operate a transmission system, direct the operation of transmission systems in the province, provide electricity or ancillary services or engage in an "electricity-related activity".

3. The ERBA will split the existing Nova Scotia Utility and Review Board ("NSUARB") into two new boards. The newly formed Energy Board ("EB") will be tasked with the regulation of energy.

The ERBA requires the EB to consider a broad array of factors when exercising its authority including:

- Competition and innovation in the provision of energy resources in the province;
- Development of a competitive electricity market;
- Safe, secure, reliable and economical energy supply in the province; and
- Sustainable development (as defined in the Environment Act [183] and sustainable prosperity as defined in the Environmental Goals and Climate Change Reduction Act [184].

iii. *Atlantic RTO – the Next Step*

With existing regional solutions for transmission grids and wholesale electricity markets represented by Regional Transmission Organizations (RTO) in North America demonstrating lower costs, improved reliability, and better environmental performance, an RTO concept applied to the Atlantic Canada region (the Atlantic RTO, or ARTO) is seen as a compelling high priority in leveraging the Clean Grid 2035 target in Canada.

The New York Independent System Operator (NYISO) and Independent System Operator New England (ISO-NE), the Regional Transmission Organizations (RTO) in the American Northeast, have been consistently demonstrating that "competitive electric markets continue to provide the most powerful and least-cost vehicle available" [49]. These RTOs have been used in their regions as an important regional development tool facilitating the transition to the clean grid. The historical ties of Atlantic Canada (specifically, the Maritimes) and New England present an important opportunity to learn the ISO-NE lessons, vision and continuous advancements to promptly build a leading North American RTO in Atlantic Canada leveraging an inter-regional integration approach of the second quarter of the 21st century.

The Atlantic RTO should be seen today as a key advancement in Canada's deep decarbonization pathways presenting best-in-class regulations that strengthen existing policies for the electricity sector. The Canadian Net-Zero Emissions Accountability Act of June 2021 shaped Canada's commitment to achieve net-zero emissions by 2050 [185].

Building on the actions in Canada's strengthened climate plan [186] and the Pan-Canadian Framework [187], the 2030 Emissions Reduction Plan [188] reflects the Canadian input to reduce emissions by 40-45 per cent from 2005 levels by 2030 (see the Emission Reduction Plan Progress Report [189] published by the Government of Canada in December 2023).

Strong connection between Deep Decarbonization and Deep Regional/Inter-regional Electricity Market Integration concepts and practices reinforces the role of the Atlantic RTO in realizing the 2030 Emissions Reduction Plan, and ensures the benefits of electricity market integration in Atlantic Canada such as improved reliability, increased demand diversity, diversity of generation mix and supply security.

The proposed Atlantic RTO is clearly seen as a key upgrade and an important component of the Canadian Electricity System addressing its generation mix, geographical structure and regulatory framework, and advancing inter-regional East-West and North-South power integration.

A special reason for supporting the Atlantic RTO by all the provinces of Atlantic Canada is the necessary and critical avoidance of the current realities of "electricity islands" in the region.

Strengthening regional grid through high voltage alternate current (AC) transmission between Nova Scotia and New Brunswick, and direct current (DC) transmission between Nova Scotia and New England, and having ARTO administer a wholesale electricity market will allow the region to benefit from an attractive set of flexible power opportunities at competitive wholesale level in:

- Generation - to better sell hydro power of Newfoundland and Labrador, and offshore wind power of Nova Scotia;
- Consumption – to better buy commercial power needed in Prince Edward Island, and industrial power (e.g., for green hydrogen) needed in Nova Scotia, and
- Bi-directional power (both generation and consumption) in Nova Scotia and New Brunswick – to address the needs of Atlantic Canada and New England.

The Atlantic RTO is seen as a strategic step in the evolution of the Atlantic Energy Gateway initiative demonstrating a new and more advanced regional leadership example in Canada. As prompt deployment and operation of the Atlantic RTO will make the region more competitive nationally and internationally, increasing cooperation and coordination by the Atlantic Provinces' electricity sectors is currently strongly required. According to a recommendation of the Canada Electricity Advisory Council's "Powering Canada: A Blueprint for Success" report in May 2024 [74], a collaborative framework for the ARTO decision-making can be used to identify and financially support inter-regional electricity transmission projects and outline their governance, cost allocation, and funding components.

Timely coordination and cooperation of the government, private, academic, and civil electricity sub-sectors on multiple levels in the Atlantic region should be promoted to achieve the ARTO deployment within the 2025-2035 timeframe. This would allow for a cooperative action to "mobilize quickly and skillfully all of the resources necessary" [190]. As a part of this cooperative action, the ARTO development and deployment would greatly benefit from the skillset of the industry in New Brunswick (with its New Brunswick System Operator created on October 1, 2004 and amalgamated with the NB Power Corporation on October 1, 2013 [191], as well as its current Transmission and System Operator [192]) and Nova Scotia (through its new Independent Energy System Operator (IESO) [38,39] as well as the skills of the Nova Scotia Power System Operator (NSPSO) [193]).

Also, the civil sub-sector (represented by the organizations that act in the public's interest but are not motivated by government or profit) that has not yet been fully involved, should be promptly engaged to leverage personal, organizational, and societal developments in the region [194]. Deep participation of Canada's indigenous peoples, or First Nations, as a part of the civil electricity sub-sector, makes compelling sense. This engagement would ensure electricity buyers/end users contribution to establishing a competitive wholesale electricity market in Atlantic Canada.

IV. Conclusions and Recommendations

1. To ensure successful steps to a low carbon economy and total electrification, *commitments to deep decarbonization in North America require regional power system integration.* Regional integration ensures a critical, productive and timely approach and strategy to provide reliable and affordable electricity anywhere, anytime. It can leverage economies, enhance energy security, and reduce greenhouse gas emissions.
2. *The most efficient solution for regional power integration, enabling competitive electricity wholesale is proven by Regional Transmission Organizations (RTO).* The RTO concept and practices ensure high efficiency and reliability of regional electricity markets and power transmission system operations. Advanced results of regional integration have been continuously demonstrated by New York Independent System Operator (NYISO) and Independent System Operator New England (ISO-NE) - the leading RTO in the American Northeast, and may be used to learn from their experience.
3. To improve power integration of regional and inter-regional electricity trade using an RTO approach, *the last frontiers for organized wholesale markets in North America should be identified, addressed and resolved.*

   In the U.S., the key RTO frontiers being currently publicly discussed are the American West and Southeast regions:

- The current work is being done in the West on establishing a more comprehensive, efficient, and dynamic system of wholesale electric competition in the region. This work has strongly driven an advanced concept of a West-wide RTO (or two RTOs) within the next few years.
- In the Southeast, the initial approach of large utilities to create real-time bilateral trade via an energy exchange market demonstrated only very small competitive steps away from the vertically integrated status quo compared to the integrated RTO practice. This approach (e.g., Southeast Energy Exchange Market (SEEM)) was not accepted by non-utility generating companies. Today, several states in the Southeast already started exploring full RTO membership.

In Canada, all provincial jurisdictions in western Canada as well as Ontario participate in or manage competitive wholesale electricity markets, and Quebec is considering the next steps in inter-regional integration. Atlantic Canada is the last RTO frontier for competitive regional electricity wholesale in the country that requires detailed public discussion.

4. *An Atlantic RTO (ARTO) proposed here manifests a key upgrade and an important component of the Canadian Electricity System* addressing its generation mix, transmission structure and regulatory framework, and advancing inter-regional East-West and North-South power integration. The ARTO would enable best-in-class regulations that strengthen existing policies for the electricity sector, and should be seen as a compelling high priority in leveraging the Clean Grid 2035 target in Canada.
5. *The Atlantic RTO is seen as a strategic step in the evolution of the Atlantic Energy Gateway (AEG)* initiative demonstrating a new and more advanced regional leadership example in Canada. Announced in 2009, the AEG initiative by March 2012 made strong advances in better understanding of the ways to move in regional clean electricity collaboration. This included regional electricity market opportunities, regional electricity system operations, regional transmission upgrade options, clean electricity resources, renewable generation supply chain opportunities in Atlantic Canada, and research, development and demonstration needs. The results of the AEG initiative were further promoted in the Clean Power Roadmap for Atlantic Canada (2022), outlining a collective vision for how the Atlantic provinces may collaborate over the coming decades to build a clean power superhighway across the region.
6. *A collaborative framework for the ARTO decision-making should be used* to increase cooperation and coordination by the Atlantic Provinces' electricity sectors. This would identify and financially support inter-regional electricity transmission projects and outline their governance, cost allocation, and funding components. According to Canada Electricity Advisory Council's report of May 2024:

"Powering Canada: A Blueprint for Success" [ARTO42], constructing a Framework for Inter-Regional Grid Infrastructure is recommended to support inter-regional electricity transmission projects.

7. *The ARTO is positioned as a critically important regional integration advancement in Canada's deep decarbonization pathways.* Strong connection between Deep Decarbonization and Deep Regional/Inter-regional Electricity Market Integration concepts and practices reinforces the role of the Atlantic RTO in realizing Canada's 2030 Emissions Reduction Plan. It ensures the benefits of electricity market integration in Atlantic Canada such as increased diversity of generation mix, improved system reliability, increased supply security and demand diversity. Prompt deployment and operation of the Atlantic RTO would make the region more competitive nationally and internationally.
8. *Timely coordination and cooperation* of the government, private, academic, and civil electricity sub-sectors on multiple levels in the Atlantic region is suggested so as to achieve the ARTO deployment within the 2025-2035 timeframe. To ensure that this coordination on multiple levels is in place, that the planned work is moving at accelerated pace, and the Atlantic RTO development and deployment milestones are met on time, socio-psychological tools for dedicated groups across all the four sectors should be used.
9. As a part of the cooperative action, the ARTO development and deployment would greatly *benefit from the existing electricity system operator skillset of the industry* in New Brunswick and Nova Scotia. Including New Brunswick Power Transmission and System Operator, Nova Scotia Power System Operator, and Nova Scotia's new Independent Energy System Operator.
10. *The civil electricity sub-sector should be promptly engaged with deep participation of Canada's First Nations* so as to leverage personal, organizational, and societal developments in the region, and to ensure that electricity buyers/end users contribute to establishing a competitive wholesale electricity market in Atlantic Canada.

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References Références Referencias

1. Morgan, G., Apt, J. and Lave, L. (June 2005). *The U.S. Electric Power Sector and Climate Change Mitigation.* Carnegie Mellon University for the Pew Center on Global Climate Change. https://www.c2es.org/document/the-u-s-electric-power-sector-and-climate-change-mitigation/
2. *Multi Dimensional Issues in International Power Grid Interconnections.* (2006). UNDESA. https://sdgs.un.org/publications/multi-dimensional-issues-international-power-grid-interconnections-16968
3. *Regional power sector integration: lessons from global case studies and a literature review: Solving energy challenges through regional cooperation.* (2010, June 1). World Bank. https://documents.worldbank.org/en/publication/documents-reports/documentdetail/915931468182329874/solving-energy-challenges-through-regional-cooperation
4. Claar, S. & Nölke, A. (2010). *Deep Integration.* D+C (Development and Cooperation) 51, 114-117.
5. Brown, P. R., & Botterud, A. (2020). *The value of Inter-Regional coordination and transmission in decarbonizing the US electricity system.* Joule, 5(1), 115–134. https://doi.org/10.1016/j.joule.2020.11.013 https://www.cell.com/joule/pdf/S2542-4351(20)30557-2.pdf
6. Bouffard, F., Debia , S., Dhaliwal , N., Pineau , P.-O. (2018). *A Decarbonized Northeast Electricity Sector: The Value of Regional Integration,* Chair in Energy Sector Management HEC Montréal, Institut de l'énergie Trottier and Trottier Institute on Sustainability in Engineering and Design, June 2018. https://energie.hec.ca/npcc/
7. Pineau, P.-O. (2021 September). *Improving integration and coordination of provincially-managed electricity systems in Canada.* HEC Montréal. Chair in Energy Sector Management. https://climateinstitute.ca/wp-content/uploads/2021/09/CICC-Improving-integration-and-coordination-of-provincially-managed-electricity-systems-in-Canada-by-Pierre-Olivier-Pineau-FINAL.pdf
8. Pineau, P.-O., Langlois-Bertrand, S. (2020). *Northeast Decarbonization: Opportunities and Challenges of Regional Electricity Sector Integration for High Renewable Penetration,* report prepared for the Northeast Electrification and Decarbonization Alliance, Chair in Energy Sector Management, HEC Montréal, April 2020. https://energie.hec.ca/wp-content/uploads/2020/04/REPORT_NE_Decarb_FINAL.pdf
https://energie.hec.ca/npcc-2/
9. Blumsack, S. (2007). *Measuring the benefits and costs of regional electric grid integration.* Energy Law Journal, 28(1), 147. http://www.felj.org/sites/default/files/docs/elj281/147-184.pdf

10. Federal Energy Regulatory Commission. (n.d.) *Order No. 888.* https://www.ferc.gov/industries-data/electric/industry-activities/open-access-transmission-tariff-oatt-reform/history-oatt-reform/order-no-888
11. Wikipedia contributors. (2024, June 30). *Regional transmission organization (North America).* Wikipedia. https://en.wikipedia.org/wiki/Regional_transmission_organization_(North_America)
12. ISO/RTO Council. (n.d.). *Coming together to create a smarter and stronger North American power grid.* https://isorto.org/
13. Giberson, M. (2024 September 10). *An RTO for the West: Opportunities and Options.* https://www.rstreet.org/research/an-rto-for-the-west-opportunities-and-options/
14. NESCOE. (2015, September 2). *Home | NESCOE.* https://nescoe.com/
15. *New England States' Vision for a clean, affordable, and reliable 21st century regional electric grid.* (2020 October). https://nescoe.com/wp-content/uploads/2020/10/NESCOE_Vision_Statement_Oct2020.pdf
16. *New England Forward Clean Energy Market (FCEM). Proposed Market Rules.* (2023 January). https://www.brattle.com/wp-content/uploads/2023/03/New-England-Forward-Clean-Energy-Market.pdf
17. *Clean Energy Markets. Supporting the Financing of New and Existing Clean Energy Resources. Forward Clean Energy Market Design Proposal.* (2023, January 4). Massachusetts Department of Energy Resources https://www.mass.gov/info-details/clean-energy-markets
18. Lee, B. (2004). *Free trade and globalization are driving the demand for north-south trade routes.* In *AIMS on Atlantica.* https://www.aims.ca/site/media/aims/Atlanticapart2.pdf
19. Kelderman, D., Atlantic Provinces Chambers of Commerce, Kelderman, D., Atlantic Institute for Market Studies, & Crowley, B. L. (2004). *Ideas matter.* https://www.aims.ca/site/media/aims/Atlanticapart1.pdf
20. Lee, B. (2004). *Plugging in the International Northeast: A Canada-US dialogue on solving regional electricity challenges.* https://www.aims.ca/site/media/aims/Atlanticapart3.pdf
21. Sinclair, S. & Jacobs, J. (2007). *Atlantica: Myths and Reality.* Canadian centre for Policy Alternatives. https://policyalternatives.ca/sites/default/files/uploads/publications/National_Office_Pubs/2007/Atlantica.pdf
22. Weil, G. L., Crowley, B. L. & Norris, B. A. (2003). *The Atlantica power market: a plan for joint action.* Atlantic Inst. for Market Studies, Halifax, NS (Canada). Funding organisation: Donner Canadian Foundation, Toronto, ON (Canada); John Dobson Foundation, Montreal, PQ (Canada) 2003. https://www.aims.ca/books-papers/the-atlantica-power-market-a-plan-for-joint-action/
23. Canada, T. *Atlantic Gateway and Trade Corridor Strategy.* (2009). https://publications.gc.ca/collections/collection_2011/tc/T22-181-2009-eng.pdf
24. Canada, T. (2007, October 14). *Canada's New Government Signs Memorandum of Understanding with Atlantic Provinces to Develop an Atlantic Gateway Strategy.* Canada.ca. https://www.canada.ca/en/news/archive/2007/10/canada-new-government-signs-memorandum-understanding-atlantic-provinces-develop-atlantic-gateway-strategy.html
25. Canada, T. (2011, March 23). *The Government of Canada announces the Atlantic Gateway and Trade Corridor Strategy.* Canada.ca. https://www.canada.ca/en/news/archive/2011/03/government-canada-announces-atlantic-gateway-trade-corridor-strategy.html
26. Martillac Limited & Thompson & Associates. (2012). *Atlantic Energy Gateway Report on regional electricity system operations.* https://energy.novascotia.ca/sites/default/files/aeg_regional_electricity_system_operations.pdf
27. *Atlantic Energy Gateway enhances regional co-operation toward a clean energy future.* (2012 September 10). https://www2.gnb.ca/content/gnb/en/departments/erd/news/news_release.2012.09.0825.html
28. *Media Advisory: Ministers to announce funding for Atlantic Canada Venture Gateway.* (n.d.). https://www.releases.gov.nl.ca/releases/2009/intrd/1015n06.htm
29. Canada, Tt. *Atlantic Gateway and Canada's Trade Corridor Strategy.* (2010) https://publications.gc.ca/collections/collection_2011/tc/T22-181-2009-eng.pdf
30. McMillan, C. (2006, November 30). *Embracing the Future: The Atlantic Gateway and Canada's Trade Corridor.* https://www.asiapacific.ca/sites/default/files/filefield/AtlanticGateway.pdf
31. Atlantic Business Magazine. (2023, August 31). *Ports of Call: the gateways to prosperity in Atlantic Canada and beyond.* https://atlanticbusinessmagazine.ca/article/ports-of-call-the-gateways-to-prosperity-in-atlantic-canada-and-beyond/
32. Canada, N. R. *Towards A Clean Power Roadmap for Atlantic Canada.* (2020 August). https://www.canada.ca/content/dam/acoa-apeca/documents/Towards%20a%20Clean%20Power%20Roadmap%20for%20Atlantic%20Canada.pdf
33. Canada, N. R. *A Clean Power Roadmap for Atlantic Canada.* (2022). https://natural-resources.canada.ca/sites/nrcan/files/energy/images/publications/2022/A%20CLEAN%20POWER%20ROADMAP%20FOR%20ATLANTIC%20CANADA-ACC.pdf
34. Department of Finance Canada. (2023, March 28). *Chapter 3: A Made-In-Canada Plan: Affordable Energy, Good Jobs, and a Growing Clean Economy.*

Budget 2023. https://www.budget.canada.ca/2023/report-rapport/chap3-en.html#a5
35. Service Canada. (2024, February 2). *Net-zero emissions by 2050.* Canada.ca. https://www.canada.ca/en/services/environment/weather/climatechange/climate-plan/net-zero-emissions-2050.html
36. Canada, N. R. (2023, August 31). *Powering Canada Forward: Building a clean, affordable, and reliable electricity system for every region of Canada.* https://natural-resources.canada.ca/our-natural-resources/energy-sources-distribution/electricity-infrastructure/powering-canada-forward-building-clean-affordable-and-reliable-electricity-system-for/25259
37. *Project of the Century - Public Policy Forum.* (2024, August 22). Public Policy Forum. https://ppforum.ca/publications/net-zero-electricity-canada-capacity/
38. Leblannm. (2024, April 5). *Bill 404 - Energy Reform (2024) Act.* Nova Scotia Legislature. https://nslegislature.ca/legc/bills/64th_1st/1st_read/b404.htm
39. *Legislation to modernize electricity system, improve regulation | Government of Nova Scotia news releases.* (2024, February 27). https://news.novascotia.ca/en/2024/02/27/legislation-modernize-electricity-system-improve-regulation
40. Binz, R. J. (2016 April). *Considerations in Establishing a Western Regional System Operator.* Prepared for the Hewlett Foundation. https://efiling.energy.ca.gov/GetDocument.aspx?tn=211283&DocumentContentId=25514
41. Wikipedia contributors. (2024a, May 7). *Open Access Same-Time Information System.* Wikipedia. https://en.wikipedia.org/wiki/Open_Access_Same-Time_Information_System
42. *U.S. Electricity Grid & Markets | US EPA.* (2024, March 27). US EPA. https://www.epa.gov/green-power-markets/us-electricity-grid-markets
43. *Electric power markets.* (n.d.). Federal Energy Regulatory Commission. https://www.ferc.gov/electric-power-market
44. Wikipedia contributors. (2024c, August 4). *Energy Policy Act of 1992.* Wikipedia. https://en.wikipedia.org/wiki/Energy_Policy_Act_of_1992
45. *The Value of Electricity Markets* (n.d.). IESO. https://www.ieso.ca/Learn/Electricity-Pricing-Explained/The-Value-of-Electricity-Markets
46. *An Introductory Guide to Electricity Markets regulated by the Federal Energy Regulatory Commission.* (n.d.). Federal Energy Regulatory Commission. https://www.ferc.gov/introductory-guide-electricity-markets-regulated-federal-energy-regulatory-commission
47. *Intertie Optimization FAQs and Implementation Principles.* (2023 October). The Brattle Group. https://www.brattle.com/wp-content/uploads/2023/10/Intertie-Optimization-FAQs-and-Implementation-Principles_v2.pdf
48. Ethier, R. & ISO-NE PUBLIC. (2021). *Transition to the future grid.* https://www.iso-ne.com/static-assets/documents/2021/11/clg_meeting_ethier_transition_to_the_future_grid_update.pdf
49. *Press Release | NYISO Releases Power Trends 2024 - NYISO.* (n.d.). NYISO. https://www.nyiso.com/-/press-release-nyiso-releases-power-trends-2024
50. England, I. N. (n.d.). *New England's Future Grid Initiative key project.* Copyright (C) 2013 ISO New England. All Rights Reserved. https://www.iso-ne.com/committees/key-projects/implemented/new-englands-future-grid-initiative-key-project
51. *Evolution of the WEIM | California ISO.* (2023, September 25). https://www.caiso.com/about/news/evolution-of-the-weim
52. *Western Services.* (n.d.). spp.org. https://www.spp.org/western-services/
53. *Markets+.* (n.d.). spp.org. https://www.spp.org/marketsplus
54. *Chen, J. (2020, May 11). Evaluating options for enhancing wholesale competition and implications for the Southeastern United States. Nicholas Institute. https://nicholasinstitute.duke.edu/publications/evaluating-options-enhancing-wholesale-competition-and-implications-southeastern*
55. R Street Institute. (2024, May 27). *The Southeast is the Last Frontier of Organized Wholesale Electricity Markets. Here are the best options moving forward - R Street Institute.* https://www.rstreet.org/commentary/the-southeast-is-the-last-frontier-of-organized-wholesale-electricity-markets-here-are-the-best-options-moving-forward/
56. R Street Institute. (2020, August 26). *How voluntary electricity trading can help efficiency in the southeast.* https://www.rstreet.org/research/how-voluntary-electricity-trading-can-help-efficiency-in-the-southeast/
57. Gheorghiu, I. (2020, August 25). Energy consulting groups value Southeast RTO potential at $384B savings by 2040. *Utility Dive.* https://www.utilitydive.com/news/energy-consulting-groups-value-southeast-rto-potential-at-384b-savings-by/584074/
58. Alvarez, G. (2024, October 17). *Economic and clean energy benefits of establishing a Southeast U.S. competitive wholesale electricity market.* Energy Innovation. https://energyinnovation.org/publication/economic-and-clean-energy-benefits-of-establishing-a-southeast-u-s-competitive-wholesale-electricity-market/
59. (2023, April 27). *Assessment of potential market reforms for south Carolinas electricity sector.* The Brattle Group. https://www.brattle.com/insights-events/publications/assessment-of-potential-market-reforms-for-south-carolinas-electricity-sector/
60. Dennis, J. (n.d.). *In the Southeast U.S., Is SEEM What It Seems, or More Utility Monopoly?*

https://blog.advancedenergyunited.org/in-the-southeast-u.s.-is-seem-what-it-seems-or-more-utility-monopoly
61. R Street Institute. (2023, July 18). *SEEMs like a problem - R Street Institute.* https://www.rstreet.org/commentary/seems-like-a-problem/
62. *SEEM filing: Limited protest and comment of public interest organizations - SACE | Southern Alliance for Clean Energy.* (2021, March 17). SACE | Southern Alliance for Clean Energy. https://cleanenergy.org/news-and-resources/seem-filing-limited-protest-and-comment-of-public-interest-organizations/
63. R Street Institute. (2024a, May 27). *Motion to intervene and comments of the R Street Institute - R Street Institute.* https://www.rstreet.org/outreach/motion-to-intervene-and-comments-of-the-r-street-institute/
64. Shober, M. (2021, October 13). *FERC deadlocked, SEEM moves forward - SACE | Southern Alliance for Clean Energy.* SACE | Southern Alliance for Clean Energy. https://www.cleanenergy.org/blog/ferc-deadlocked-seem-moves-forward/
65. *ELibrary.* (n.d.). https://elibrary.ferc.gov/eLibrary/docinfo?accession_number=20211013-3010
66. Kimberly D. Bose. (2021). *Notice of Filing Taking Effect by Operation of Law.* https://southeastenergymarket.com/wp-content/uploads/Notice-re-SEEM-Effective-by-OOL-10.13.2021-ER21-1111.pdf
67. Patton, D. (2023, June 18). *Southeast Energy Exchange Market | Potomac Economics.* https://www.potomaceconomics.com/markets-monitored/southeast-energy-exchange-market/
68. *Commissioner Clements' Dissent in Alabama Power Company, et al.* (2024, June 14). Federal Energy Regulatory Commission. https://ferc.gov/news-events/news/commissioner-clements-dissent-alabama-power-company-et-al
69. Howland, E. (2024, June 18). FERC reconsiders Southeast Energy Exchange Market approval. *Utility Dive.* https://www.utilitydive.com/news/ferc-southeast-energy-exchange-market-seem-hearing/719221/
70. *Pathways to deep decarbonization - 2015 Report Executive Summary.* (2014). IDDRI. https://www.iddri.org/en/publications-and-events/report/pathways-deep-decarbonization-2015-report-executive-summary
71. Bataille, C., Sawyer, D., Melton, N., & CMC Research Institutes Inc. (2015). Pathways to deep decarbonization in Canada. In *Phase 2 Report: Draft Final for Comment.* https://cmcghg.com/wp-content/uploads/2015/07/Final-Canada-DDPP-Country-Report-July-14.pdf
72. Energy and Environmental Economics, Inc. (E3). (2022). *Research Review: The role of Transmission in the context of Deep Decarbonization.* https://www.electricity.ca/files/reports/english/Final-Electricity-Canada-Net-Zero-Report-7.pdf
73. Ivey Energy Policy and Management Centre & Ivey Business School. (2022). *Electrification and investment in electricity infrastructure.* https://landing.ivey.ca/media/3797288/iveyenergycentre_electrification_and_investment_final.pdf
74. *Powering Canada: A blueprint for success – Canada Electricity Advisory Council: Final report – Energy Modelling Hub.* (n.d.). https://cme-emh.ca/en/powering-canada-a-blueprint-for-success-canada-electricity-advisory-council-final-report/
75. *Projects of common interest | www.acer.europa.eu.* (n.d.). https://www.acer.europa.eu/electricity/infrastructure/projects-common-interest
76. *PCI examples and their benefits.* (n.d.). Energy. https://energy.ec.europa.eu/topics/infrastructure/projects-common-interest-and-projects-mutual-interest/pci-examples-and-their-benefits_en
77. Lew, D., Bakke, J., Bloom, A., Brown, P., Caspary, J., Clack, C., Miller, N., Orths, A., Silverstein, A., Simonelli, J., & Zavadil, R. (2021). Transmission planning for 100% clean electricity: Enabling clean, affordable, and reliable electricity. *IEEE Power and Energy Magazine, 19*(6), 56–66. https://doi.org/10.1109/mpe.2021.3104127
78. *Deep Decarbonization in the Northeast United States and Expanded Coordination with Hydro-Québec - Sustainable Development Solutions Network.* (2018, April 9). https://www.unsdsn.org/resources/deep-decarbonization-in-the-northeast-united-states-and-expanded-coordination-with-hydro-quebec/
79. *Assessing the multi-value benefits of transmission expansion - University of Victoria.* (2024, July 23). UVic.ca. https://www.uvic.ca/research/centres/iesvic/news-events/energybriefs/current-briefs/assessing-the-multi-value-benefits-of-transmission-expansion.php
80. Nordic co-operation on energy. (n.d.). The Nordic Council of Ministers. https://www.norden.org/en/information/nordic-co-operation-energy
81. Nordisk Ministerråd. (2020). *The Nordic Region – towards being the most sustainable and integrated region in the world: Action Plan for 2021 to 2024.* DIVA. https://norden.diva-portal.org/smash/record.jsf?pid=diva2%3A1508295&dswid=4169%20%20https://norden.diva-portal.org/smash/get/diva2:1508295/FULLTEXT01.pdf
82. Nordisk Ministerråd. (2024). *Nordic Co-operation Policy for Energy 2025–2030.* DIVA. https://norden.diva-portal.org/smash/record.jsf?pid=diva2%3A1907864&dswid=-469
83. Pineau, P.-O. (2013). *Fragmented Markets: Canadian Electricity Sectors' Underperformance.* Evolution of Global Electricity Markets: New Paradigms, New Challenges, New Approaches. Pages 363-392 https://doi.org/10.1016/B978-0-12-397891-2.00013-4

84. Wigg, B. (2023, October 24). *A collaborative for greater coordination and integration among the electric grids of eastern Canada and the northeastern United States.* Regulatory Assistance Project. https://www.raponline.org/knowledge-center/collaborative-greater-coordination-integration-electric-grids-eastern-canada-northeastern-united-states/
85. Pineau, P.-O. (2015, November 20). The Benefits of Integrating Electricity Markets – Why and How Canadian Provinces Should Reform their Electricity Sector. https://www.mun.ca/economics/media/production/memorial/academic/faculty-of-humanities-and-social-sciences/economics/media-library/more/events/Pineau_Presentation_Nov_2015.pdf
86. Teusch, J. (2012). Renewables and the EU internal electricity market: The case for an arranged marriage. *SSRN Electronic Journal.* https://doi.org/10.2139/ssrn.2028908
87. De Villemeur, E. B., & Pineau, P. (2011). Regulation and electricity market integration: When trade introduces inefficiencies. *Energy Economics, 34*(2), 529–535. https://doi.org/10.1016/j.eneco.2011.12.004
88. Atlantic Clean Power Planning Committee, Bharadwaj, S., Yuan, M., Ouyang, J., Levine, M., Schlag, N., Shaw, R., Li, C., & Olson, A. (2021). *Potential benefits of regional coordination in a Low-Carbon future.* https://secondstreet.org/wp-content/uploads/2023/11/NB-NB-Natural-Resources-and-Energy-Development.-FOI-1pdf.pdf
89. Pineau, P.-O. (2024). Regional collaboration and infrastructure optimization in energy modelling. In *Atlantic Canadian Conference on Energy System Modelling* [Conference Presentation]. Energy Modelling Hub and Net Zero Atlantic. https://netzeroatlantic.ca/sites/default/files/2024-07/Pierre%20Olivier%20Pineau%20Presentation.pdf
90. Wikipedia contributors. (2024d, August 13). *Alberta Electric System Operator.* Wikipedia. https://en.wikipedia.org/wiki/Alberta_Electric_System_Operator
91. AESO 20th anniversary. (n.d.) AESO. https://www.aeso.ca/aeso/about-the-aeso/aeso-20th-anniversary/
92. *About the AESO.* (n.d.). AESO. https://www.aeso.ca/aeso/about-the-aeso/
93. *Net-Zero Emissions Pathways.* (n.d.). AESO. https://www.aeso.ca/future-of-electricity/net-zero-emissions-pathways/
94. Wikipedia contributors. (2024e, September 6). *Independent electricity system operator.* Wikipedia. https://en.wikipedia.org/wiki/Independent_Electricity_System_Operator
95. *Connecting Today. Powering Tomorrow.* (n.d.). IESO. https://www.ieso.ca/
96. *2024 Annual Planning Outlook and Emissions Update.* (n.d.). IESO. https://www.ieso.ca/Powering-Tomorrow/2024/Six-Graphs-and-a-Map-2024-Annual-Planning-Outlook-and-Emissions-Update
97. *AESO Materials | Market Pathways | AESO Engage.* (2024, January 31). https://www.aesoengage.aeso.ca/37884/widgets/156642/documents/125518
98. *AESO Net-Zero Emissions Pathways Report.* (2022). https://www.aeso.ca/assets/AESO-Net-Zero-Emissions-Pathways-Report-July7.pdf
99. *Net-Zero Emissions Pathways.* (n.d.-b). AESO. https://www.aeso.ca/future-of-electricity/net-zero-emissions-pathways/
100. *Reliability Requirements Roadmap.* (n.d.). AESO. https://www.aeso.ca/future-of-electricity/reliability-requirements-roadmap
101. *MSInformation.* (n.d.). https://www.aeso.ca/assets/Uploads/future-of-electricity/AESO-2023-Reliability-Requirements-Roadmap.pdf
102. *AESO Materials | Market Pathways | AESO Engage.* (n.d.-b). https://www.aesoengage.aeso.ca/37884/widgets/156642/documents/125518
103. *AESO Materials | REM Technical Design | AESO Engage.* (n.d.). https://www.aesoengage.aeso.ca/42905/widgets/179261/documents/128072
104. *REM Technical Design.* (n.d.). AESO Engage. https://www.aesoengage.aeso.ca/rem-technical-design
105. *Market Renewal.* (n.d.). IESO. https://ieso.ca/en/Market-Renewal
106. *Overview of Market Renewal* (n.d.). IESO. https://ieso.ca/Market-Renewal/Background/Overview-of-Market-Renewal
107. *FERC Order No. 2222 Explainer: Facilitating Participation in Electricity Markets by Distributed Energy Resources.* (n.d.). Federal Energy Regulatory Commission. https://www.ferc.gov/ferc-order-no-2222-explainer-facilitating-participation-electricity-markets-distributed-energy
108. *Procuring Services from Distributed Energy Resources. Part 1 – Foundational Topics: Grid Services, Coordination Frameworks, Value Stacking Scenarios.* (2023 December). EPRI. https://www.ieso.ca/-/media/Files/IESO/Document-Library/engage/yrnwa/yrnwa-20240611-1-Foundational-Topics-3002028579.pdf
109. *DER Roadmap.* (n.d.). IESO. https://www.ieso.ca/Get-Involved/Innovation/Distributed-Energy-Resources/DER-Roadmap
110. *Distributed Energy Resources Market Vision and Design Project.* (n.d.). IESO. https://www.ieso.ca/en/Sector-Participants/Engagement-Initiatives/Engagements/Distributed-Energy-Resources-Market-Vision-and-Design-Project
111. *Distributed Energy Resources (DER) Market Vision and Design Project –Stakeholder Feedback and IESO Response.* (2022, June 22). IESO. https://www.ieso.ca/-/media/Files/IESO/Document-Library/

engage/dermvdp/dermvdp-20220714-response-to-feedback.pdf

112. *Distributed Energy Resources (DER) -Market Vision and Design Project: Recommendations for Enhanced Models.* (2023, January 25). IESO. https://www.ieso.ca/-/media/Files/IESO/Document-Library/engage/dermvdp/dermvdp-20230125-presentation.pdf
113. *Operating Reserve Market Review Rule amendments.* (n.d.). AESO Engage. https://www.aesoengage.aeso.ca/operating-reserve-market-review-rule-amendments
114. *Powerex Corp. a Wholly Owned Subsidiary of BC Hydro.* (n.d.). https://powerex.com/about-us/who-we-are
115. California Independent System Operator Corporation. (2018). Petition for Limited Tariff Waiver and Request for Expedited Consideration. In *Federal Energy Regulatory Commission.* https://www.caiso.com/Documents/Apr10_2018_Petition_LimitedTariffWaiver-PowerexReversalFlow_ER18-1339.pdf
116. *Powerex's EIM participation.* (2017). https://www.caiso.com/documents/powerexpresentation-powerexeimimplementationagreementoverview.pdf
117. *Powerex Commits to Markets+.* (2022 November). Powerex. https://powerex.com/sites/default/files/2022-11/Powerex%20Commits%20to%20Markets%2B.pdf
118. *SPP confirms timing of Markets+ implementation milestones; Powerex commits to Markets+ participation and funding.* (n.d.). spp.org. https://www.spp.org/news-list/spp-confirms-timing-of-marketsplus-implementation-milestones-powerex-commits-to-marketsplus-participation-and-funding/
119. Kleckner, T. (2024, March 26). SPP Board approves Markets+ Phase 1 tariff. *RTO Insider.* https://www.rtoinsider.com/74592-spp-board-approves-markets-phase-1-tariff/
120. Walton, R. (2024, April 2). SPP files Markets+ tariff in 'significant step' to expanding Western market options. *Utility Dive.* https://www.utilitydive.com/news/spp-files-west-markets-tariff-day-ahead-FERC/711952
121. *Southwest Power Pool Project.* (n.d.). https://www.saskpower.com/our-power-future/infrastructure-projects/construction-projects/planning-and-construction-projects/southwest-power-pool-project
122. *Southwest Power Pool welcomes first international member.* (n.d.). spp.org. https://www.spp.org/news-list/southwest-power-pool-welcomes-first-international-member/
123. Manitoba Hydro. (n.d.). *Coordinating Member Sector Overview.* https://cdn.misoenergy.org/20210913%20AC%20Item%2002%20Coordinating%20Member%20Sector%20Profile587375.pdf
124. *Services Internet indisponibles.* (n.d.). Hydro-Québec. https://www.hydroquebec.com/transenergie/fr/
125. La Flèche, E. R. (2022, June 24). *Hydro-Québec and its U.S. transmission Projects - energy regulation quarterly.* Energy Regulation Quarterly. https://energyregulationquarterly.ca/articles/hydro-quebec-and-its-u-s-transmission-projects#sthash.xnPZUoa6.dpbs
126. *Pfeifenberger, J., Graham, K., DOE, Tufts, & DeLosa, P. (2024). Cost-Effective Transmission between Canada and the US Northeast. In Bridging the Power Gap Webinar (pp. 1–8). https://www.brattle.com/wp-content/uploads/2024/10/Cost-Effective-Transmission-between-Canada-and-the-US-Northeast.pdf*
127. Lamson, J. (2024, April 24). *Québec, New England see shifting role for Canadian hydropower.* RTO Insider. https://www.rtoinsider.com/72093-quebec-new-england-shifting-role-hydropower/
128. Yuan, M., Tapia-Ahumada, K., & Reilly, J. (2021). The role of cross-border electricity trade in transition to a low-carbon economy in the Northeastern U.S. *Energy Policy, 154,* 112261. https://doi.org/10.1016/j.enpol.2021.112261
129. Pineau, P. (2012). *Integrating electricity sectors in Canada: Good for the environment and for the economy.* https://www.semanticscholar.org/paper/Integrating-electricity-sectors-in-Canada%3A-Good-for-Pineau/b8d582b485bcbdfa4c9b5b281c4e31c52c1de00a
130. De Villemeur, E. B., & Pineau, P. (2015). Integrating Thermal and Hydro Electricity Markets: Economic and Environmental Costs of not Harmonizing Pricing Rules. *The Energy Journal, 37*(1), 77–100. https://doi.org/10.5547/01956574.37.1.edev
131. Rodríguez-Sarasty, J.A., Debia, S., Pineau P.-O. (2021 May). Deep decarbonization in Northeastern North America: The value of electricity market integration and hydropower Energy Policy Volume 152. https://www.sciencedirect.com/science/article/abs/pii/S0301421521000793
132. Pineau, P.-O., Rodríguez, J. A., & Debia, S. (2021). *Les bénéfices de l'intégration des marchés de l'électricité dans le Nord-Est de l'Amérique.* https://energie.hec.ca/wp-content/uploads/2021/03/PPT_Pineau_2021-03-29.pdf
133. *Implementation Plan.* (n.d.). Gouvernement Du Québec. https://www.quebec.ca/en/government/policies-orientations/plan-green-economy/implementation
134. *2030 Plan for a green economy.* (n.d.). Gouvernement Du Québec. https://www.quebec.ca/en/government/policies-orientations/plan-green-economy
135. Action Plan 2035. (2023). Hydro-Quebec. https://www.hydroquebec.com/data/a-propos/pdf/action-plan-2035.pdf

136. *With demand set to surge, Hydro-Québec looks to expand transmission capacity.* (2024, November 5). CBC. https://www.cbc.ca/news/canada/montreal/hydro-quebec-transmission-lines-1.7374047
137. Hydro-Québec. (n.d.). *Transmitting the Energy of Our Goals: Hydro-Québec is upgrading its transition system...* Hydro-Québec. https://news.hydroquebec.com/en/press-releases/2133/transmitting-the-energy-of-our-goals-hydro-quebec-is-upgrading-its-transition-system-for-a-successful-energy-transition/
138. *Services Internet indisponibles.* (n.d.-b). Hydro-Québec. https://www.hydroquebec.com/projects/strengthening735kv/
139. *Data specification for Hydro-Québec* (2024, October 1). Hydro-Quebec. https://www.hydroquebec.com/data/transenergie/pdf/specification-de-donnees-en.pdf
140. *Bill 69, An Act to ensure the responsible governance of energy resources and to amend various legislative provisions - National Assembly of Québec.* (n.d.). https://www.assnat.qc.ca/en/travaux-parlementaires/projets-loi/projet-loi-69-43-1.html
141. *Québec Amps Up its Electricity Regulation Framework.* (2024, June 21). McCarthy. https://www.mccarthy.ca/en/insights/blogs/canadian-energy-perspectives/quebec-amps-its-electricity-regulation-framework
142. Dionne, P., Nolet-Lévesque, F., Durocher, C. R., Gaudette-Richard, S., & Hébert-Ferrat, V. (2024, September 3). *Bill 69: A new era for the Québec energy sector.* BLG. https://www.blg.com/en/insights/2024/09/projet-de-loi-69-une-nouvelle-ere-pour-le-secteur-de-lenergie-au-quebec
143. Mousseau, N. (2024, September 18). *Québec is preparing its energy transition.* Canada's National Observer. https://www.nationalobserver.com/2024/09/16/opinion/quebec-preparing-its-energy-transition
144. Toolkit, W. E. (2011, February 22). *News Archives.* Government of Prince Edward Island. Atlantic Energy Ministers agree to speed up regional co-operation efforts. https://www.gov.pe.ca/webarchive/index.php?number=news&dept=&newsnumber=7598&lang=E
145. Regional Clean and Renewable Energy Market Opportunities Navigant Sep 7, 2012 https://energy.novascotia.ca/sites/default/files/aeg_regional_clean_and_renewable_energy_market_opportunities.pdf
146. Navigant Consulting Ltd. (2012). *Regional clean and Renewable energy market opportunities.* https://energy.novascotia.ca/sites/default/files/aeg_regional_clean_and_renewable_energy_market_opportunities.pdf
147. *Balancing Study Report: A Report on Potential Savings in the Case of a Common Unit Commitment and Dispatch Function for Atlantic Canada.* (2012, June 15). https://energy.novascotia.ca/sites/default/files/aeg_system_balancing_modeling.pdf https://energy.novascotia.ca/document-library/document/balancing-study-report-report-potential-savings-case-common-unit
148. Maritime Electric Company Limited, Younker, R., New Brunswick Power Holding Corporation, Bourque, M., New Brunswick System Operator, Brown, S., Newfoundland & Labrador Hydro, Moulton, R., Nova Scotia Power Incorporated, Rangaswamy, K., Sampson, M., ABB Ventyx, & Hughes, E. (2012). *Atlantic Energy Gateway Resource Development Modelling Study.* https://energy.novascotia.ca/sites/default/files/aeg_resource_development_modeling.pdf
149. Concentric Energy Advisors. (2012). *Renewable Generation supply chain opportunities in Atlantic Canada.* https://netzeroatlantic.ca/sites/default/files/2019-05/Renewable%20Generation%20Supply%20Chain%20Opportunities%20in%20Atlantic%20Canada%20%E2%80%93%20Final%20Report.pdf
150. AEG_research_development_and_demonstration Patey, P., Chandler, C., Atlantic Canada Opportunities Agency, Maxis Energy Solutions, & SLR Consulting (Canada) Ltd. (2012). *Research, development and demonstration: challenges and opportunities.* https://energy.novascotia.ca/sites/default/files/aeg_research_development_and_demonstration.pdf
151. *Atlantic Region Summary for Policy Makers: Regional Electricity Cooperation and Strategic Infrastructure.* (2018). NRCan. https://publications.gc.ca/collections/collection_2019/rncan-nrcan/M134-50-2018-eng.pdf
152. *Atlantic Loop no longer part of Nova Scotia plan to hit 2030 renewable energy targets.* (2023, October 11). Atlantic. https://atlantic.ctvnews.ca/atlantic-loop-no-longer-part-of-nova-scotia-plan-to-hit-2030-renewable-energy-targets-1.6597337
153. Canada, N.R. (2023). *Joint Policy Statement on Developing and Transmitting Clean, Reliable and Affordable Power in Nova Scotia and New Brunswick.* https://www.canada.ca/en/natural-resources-canada/news/2023/10/joint-policy-statement-on-developing-and-transmitting-clean-reliable-and-affordable-power-in-nova-scotia-and-new-brunswick.html
154. Canada, N.R. (2023). *Governments of Canada, Nova Scotia and New Brunswick Show Progress Toward Phasing Out Coal by 2030 and Expanding Their Clean, Reliable and Affordable Electricity Grids.* https://www.canada.ca/en/natural-resources-canada/news/2023/10/governments-of-canada-nova-scotia-and-new-brunswick-show-progress-toward-phasing-out-coal-by-2030-and-expanding-their-clean-reliable-and-affordable.html
155. *Nova Scotia's 2030 Clean Power Plan.* (2023). Government of Nova Scotia. https://beta.novasco

tia.ca/sites/default/files/documents/1-3582/nova-scotia-clean-power-plan-presentation-en.pdf
156. *Muskrat Falls Project Asset Update.* (2021, November 29). Newfoundland & Labrador Hydro. http://www.pub.nf.ca/indexreports/From%20NLH%20-%20Muskrat%20Falls%20Project%20Asset%20Update%20-%202021-11-29.PDF
157. *Muskrat Falls hydroelectric project in N.L. considered commissioned: CEO.* (2023, April 12). The Canadian Press. https://www.thecanadianpressnews.ca/environment/muskrat-falls-hydroelectric-project-in-n-l-considered-commissioned-ceo/article_be98f9f6-b949-50f1-8c8d-3b504f4cb046.html
158. *Lower Churchill Project | Nalcor Operations | Nalcor Energy.* (n.d.). https://web.archive.org/web/20161129063257/http://www.nalcorenergy.com/Lower-Churchill-Project.asp
159. Wikipedia contributors. (2024c, July 30). *Muskrat Falls Generating Station.* Wikipedia. https://en.wikipedia.org/wiki/Muskrat_Falls_Generating_Station
160. *ATCO | Labrador Island Link.* (n.d.). https://www.atco.com/en-ca/about-us/projects/labrador-island-link.html
161. *Maritime link infrastructure.* (n.d.). Emera Newfoundland and Labrador. https://www.emeranl.com/maritime-link/maritime-link-infrastructure
162. *Maritime Link | Hitachi Energy.* (n.d.). https://www.hitachienergy.com/ca/en/news-and-events/customer-success-stories/maritime-link
163. *The rise of utility-scale storage in Canada.* (n.d.). https://www.ibanet.org/Canada-utility-scale-storage
164. Canada, E. a. C. C. (2024, March 11). Cutting the ribbon on the largest battery energy storage system in New Brunswick. *Canada.ca.* https://www.canada.ca/en/environment-climate-change/news/2024/03/cutting-the-ribbon-on-the-largest-battery-energy-storage-system-in-new-brunswick.html
165. *Powering our Economy and the World with Clean Energy. Our Path Forward to 2035.* (2023 December). Province of New Brunswick. https://www2.gnb.ca/content/dam/gnb/Corporate/Promo/energy-energie/GNB-CleanEnergy.pdf
166. Grant, T. (2024, June 17). Regulator OKs Nova Scotia Power's $354M battery project. *CBC.* https://www.cbc.ca/news/canada/nova-scotia/nsp-battery-storage-system-approved-1.7235197?__vfz=medium%3Dsharebar
167. *Net-Zero - Wind, hydro and gas.* (Jan 31, 2024). Atlantic Economic Council. https://atlanticeconomiccouncil.ca/page/NetZeroExistingtechnologyJan2024
168. Canada, N. R. (2022). *Clean Power Roadmap for Atlantic Canada.* Government of Canada. https://natural-resources.canada.ca/energy/electricity-infrastructure/electricity-infrastructure-publications/clean-power-roadmap-for-atlantic-canada/24190
169. Government of Nova Scotia. (May 2023). *Nova Scotia Offshore Wind Roadmap.* https://novascotia.ca/offshore-wind/docs/offshore-wind-roadmap.pdf
170. Nicholson, P. & Public Policy Forum. (2023). Catching the wind. In *Public Policy Forum.* Public Policy Forum. https://ppforum.ca/wp-content/uploads/2023/10/CatchingTheWind-AtlanticCanadaEnergySuperpower-PPF-Oct2023-EN.pdf
171. Canada, N. R. (2023, May 31). The accord acts and the joint management regimes in Nova Scotia and Newfoundland and Labrador. *Canada.ca.* https://www.canada.ca/en/natural-resources-canada/news/2023/05/the-accord-acts-and-the-joint-management-regimes-in-nova-scotia-and-newfoundland-and-labrador.html
172. *C-49 (44-1) - LEGISinfo - Parliament of Canada.* (n.d.). LEGISinfo. https://www.parl.ca/legisinfo/en/bill/44-1/c-49
173. Canada, N. R. (2024, August 29). *Nova Scotia Regional Energy and Resource Table – Framework for collaboration on the path to Net-Zero.* https://natural-resources.canada.ca/climate-change/regional-energy-and-resource-tables/regional-energy-and-resource-tables-nova-scotia/nova-scotia-regional-energy-and-resource-table-framework-for-collaboration-on-the-pat/26111
174. Power Advisory LLC, NEMOEC Coalition, Power Advisory LLC, NEMOEC Coalition, Power Advisory, DNV, Watson, A., & Mike. (2023). *A new England - Maritimes offshore energy corridor builds regional resilience for a clean energy future.* https://nemoec.com/wp-content/uploads/2023/05/Power-Advisory-NEMOEC-Shared-Tx-White-Paper_final.pdf
175. *Green Hydrogen Action Plan.* (n.d.). https://novascotia.ca/green-hydrogen/docs/green-hydrogen-action-plan.pdf
176. *Canada-Germany Energy Partnership.* (2024, September 11). Canada-Germany Energy Partnership. https://canada-germany-energy-partnership.org/
177. Canada, N. R. (2022, August 23). Canada and Germany Sign Agreement to Enhance German Energy Security with Clean Canadian Hydrogen. *Canada.ca.* https://www.canada.ca/en/natural-resources-canada/news/2022/08/canada-and-germany-sign-agreement-to-enhance-german-energy-security-with-clean-canadian-hydrogen.html
178. Canada, N. R. (2024a, March 18). Government of Canada and Germany Land arrangement Securing early market access for clean Canadian hydrogen. *Canada.ca.* https://www.canada.ca/en/natural-resources-canada/news/2024/03/government-of-canada-and-germany-land-agreement-securing-early-market-access-for-clean-canadian-hydrogen.html
179. *EverWind Point Tupper Green Hydrogen/Ammonia Project – Phase 1.* (n.d.). https://novascotia.ca/nse/

ea/everwind-point-tupper-green-hydrogen-ammonia-project/
180. *Bear Head Energy Green Hydrogen and Ammonia Production, Storage and Loading Facility | Environmental Assessment.* (n.d.). https://novascotia.ca/nse/ea/bear-head-energy/
181. Nova Scotia Clean Electricity Solutions Task Force *Modernizing energy: From transition to transformation.* (2024). https://cetaskforce.ca/wp-content/uploads/2024/02/FInal-Report-February-23.pdf
182. Aharvey. (2024, April 5). *Reset for renewables: Nova Scotia overhauls energy regulation and governance in advance of influx of renewable energy - Stewart McKelvey.* Stewart McKelvey. https://stewartmckelvey.com/thought-leadership/reset-for-renewables-nova-scotia-overhauls-energy-regulation-and-governance-in-advance-of-influx-of-renewable-energy/
183. *Environment Act.* (2023). Province of Nova Scotia. https://nslegislature.ca/sites/default/files/legc/statutes/environment.pdf
184. Environmental Goals and Climate Change Reduction Act. (2021 October). Province of Nova Scotia. https://novascotia.ca/nse/progress-report/
185. Service Canada. (2024, February 2). Net-zero emissions by 2050. Canada.ca. Service Canada. (2024, September 3). *Net-zero emissions by 2050.* Canada.ca. https://www.canada.ca/en/services/environment/weather/climatechange/climate-plan/net-zero-emissions-2050.html
186. Service Canada. (2021, April 8). *A healthy environment and a healthy economy.* Canada.ca. https://www.canada.ca/en/services/environment/weather/climatechange/climate-plan/climate-plan-overview/healthy-environment-healthy-economy.html
187. Service Canada. (2016, December 9). Pan-Canadian Framework on Clean Growth and Climate Change. https://www.canada.ca/en/services/environment/wather/climatechange/pan-canadian-framework.html
188. Service Canada. (2023, December 7). *2030 Emissions Reduction Plan: Clean air, Strong economy.* Canada.ca. https://www.canada.ca/en/services/environment/weather/climatechange/climate-plan/climate-plan-overview/emissions-reduction-2030.html
189. Service Canada. (2024a, September 3). *2023 Progress Report on the 2030 Emissions Reduction Plan.* Canada.ca. https://www.canada.ca/en/services/environment/weather/climatechange/climate-plan/climate-plan-overview/emissions-reduction-2030/2023-progress-report.html
190. Beck, D. (2014 September). *Sustainable Cultures, Sustainable Planet: A Values System Perspective on Constructive Dialogue and Cooperative Action.* Integral Leadership Review. http://integralleadershipreview.com/11883-916-sustainable-cultures-sustainable-planet-values-system-perspective-constructive-dialogue-cooperative-action/
191. Wikipedia contributors. (2022, August 22). *New Brunswick System Operator.* Wikipedia. https://en.wikipedia.org/wiki/New_Brunswick_System_Operator
192. Transmission & System Operator. (n.d.). New Brunswick Power. https://tso.nbpower.com/public/en/op/
193. Nova Scotia Power System Operator. (2007). Market Procedure MP-05 Amendments to market Rules, Standards, Codes and Market Procedures. In *Market Procedure* (Report MP-05; Issue 02, pp. 2–7). https://www.nspower.ca/docs/default-source/pdf-to-upload/mp-05.pdf?sfvrsn=56273bc1_0
194. Pavlovski, A. (n.d.). The future grid in a dynamic spiral. *Global Journal of Researches in Engineering, 23–23*(4). https://globaljournals.org/GJRE_Volume23/3-The-Future-Grid-in-a-Dynamic-Spiral.pdf
195. England, I. N. (n.d.-b). *Strategic Plan.* Copyright (C) 2013 ISO New England. All Rights Reserved. https://www.iso-ne.com/about/corporate-governance/strategic-plan?utm_source=isone&utm_medium=aboutus
196. *Grid of the future.* (n.d.). NYISO. https://www.nyiso.com/grid-of-the-future
197. Côté, F., Sosland, D. L., & The Northeast Grid Planning Forum. *(2024). Canada's electricity grid and network* (By Nergica & Acadia Center). https://www.ourcommons.ca/Content/Committee/441/RNNR/Brief/BR13226671/br-external/AcadiaCenter-Nergica-e.pdf
198. Impact Assessment Agency of Canada. (2024a, November 8). *Regional assessment of offshore wind development in Nova Scotia.* Canadian Impact Assessment Registry. https://iaac-aeic.gc.ca/050/evaluations/proj/83514
199. Impact Assessment Agency of Canada. (2024, November 19). *Final Agreement and Terms of Reference between the Governments of Canada and Nova Scotia.* Canadian Impact Assessment Registry. https://iaac-aeic.gc.ca/050/evaluations/document/147038?culture=en-CA
200. Impact Assessment Agency of Canada. (2024b, November 19). *Draft regional assessment report.* Canadian Impact Assessment Registry. https://iaac-aeic.gc.ca/050/evaluations/document/159507?culture=en-CA
201. *Interconnections SEAM Study.* (n.d.). Energy Analysis | NREL. https://www.nrel.gov/analysis/seams.html
202. Daymark Energy Advisors. (2024). US Northeastern RTOs ISO-NE/NYISO/PJM inter-regional transmission planning landscape (By Daymark Energy Advisors). https://nescoe.com/wp-content/uploads/2024/06/Report-Interregional-Transmission-Planning.pdf

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By Md. Rakibul Islam, Md. Mehedi Hasan Rumel & Khorshed Alam
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Strictly as per the compliance and regulations of:

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Md. Rakibul Islam [α], Md. Mehedi Hasan Rumel [σ] & Khorshed Alam [ρ]

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I. Introduction

As the world is developing day by day the energy consumption is also increasing. We need much electricity than before but our sources are limited. Fossil fuel is limited and decreasing. Besides Fossil fuel based conventional power generation system emits a large number of greenhouse gases (CFC) which creates contamination of the environment. Sources of renewable energy can be the substitute remedy to generate power. Sun is where all energy comes from resources. Solar panel technology is one of the greatest techno-logy in renewable energy technology.

Various kinds of solar cells are employed to produce energy. Some of them are, silicon solar cell with crystals, Amorphous Silicon Photovoltaic, Cd-Te photovoltaic cell, CIGS Photovoltaic cell, Multi-junction Photovoltaic cell, Tandem Photovoltaic cell, Perovskite Solar Cell etc. Perovskite Solar Cell is one of the largest technologies in the world. Many researchers are doing their research to raise the efficiency of this Photovoltaic cell.

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II. Literature Review

Solar cell technology can be categorized into three generations. The initial cohort photovoltaic cells are wafer-oriented for example crystalline silicon photovoltaic cell. The solar cells of the second generation are organic solar cells that are based on thin films and belong to the third generation [1]. Perovskite solar cells are very efficient for future solar cell technology. Perovskite material can be efficiently used in solar cell, supercapacitor etc. The Perovskite solar cells have an efficiency of greater than 20%. [2], [3]. No other kind of photovoltaic device has shown the startling rate of device efficiency growth in the past. Though the efficiency is increasing, it is quite challenging to achieve this efficiency in large scale industrial applications. The durability of this technology over the long term continues to be a concern [4].

Perovskite solar cell technology can be constructed using both organic based solar cell and Inorganic based solar cell. Organic - inorganic hybrid perovskite material is showing better efficiency than the inorganic perovskite material is recent researchers. Research efforts in hybrid organic-inorganic perovskites have intensified significantly. This emerging solar cell technology has shown rapid progress, with frequent advancements in power conversion efficiency percentages [5]. Notably, a study conducted in 2009 focused on a cell utilizing $CH_3NH_3SnBr_3$, demonstrating a high photo-voltage of 0.96 V and an efficiency value of 3.8% [6].

Two years later, in 2011, a perovskite cell with nanocrystals sized at 2-3 nm ($CH_3NH_3SnI_3$) achieved a solar electric efficiency of 6.54% [7]. By the year 2023, significant progress was observed, with energy conversion efficiencies reaching an impressive 16.2% [8]. In that same year, optimizing the treatment conditions for the Tio_2 layer resulted in a Power Conversion Efficiency (PCE) of 19.3% [9],[10]. After nearly five years of dedicated research, the efficiency surpassed 22% [3]. In recent research, the PCE of perovskite Solar cells are employing a variety of materials in an expanding manner and advanced technology.

III. Methodology

We employ utilizing numerical simulation with SCAPS-1D aims to improve the efficiency of a lead-free planar heterostructure perovskite solar cell with an n-i-p configuration. The device comprises an intrinsic layer made of methyl ammonium tin iodide ($MASnI_3$) serving as both the i-layer and p-layer, while Spiro-OMeTAD is used for the p-layer. The n-layer is composed of SnO_2. The goal is to optimize the design and parameters through simulation, enhancing the overall performance of the solar cell. [11].

A software program called SCAPS is used to simulate the electrical and optical characteristics of solar cells. It's frequently used to evaluate and improve many kinds of solar cell devices, such as silicon, organic material, and perovskites-based ones. [13]

There are multiple steps in the SCAPS simulation, and the particular techniques used can change depending on the kind of solar cell under study. Here's a broad rundown.

a) *Numerical Modeling*

The design is a standard CH3NH3SnI3, based on PV cell structure. Figure 1, shows the cell is composed of an absorber layer, an n-type (ZnO), which represents an ETL layer, placed at the bottom, and the top of the p-type (Spiro-OMeTAD/P_3HT/Cu_2O), which represents an HTL layer. [12]

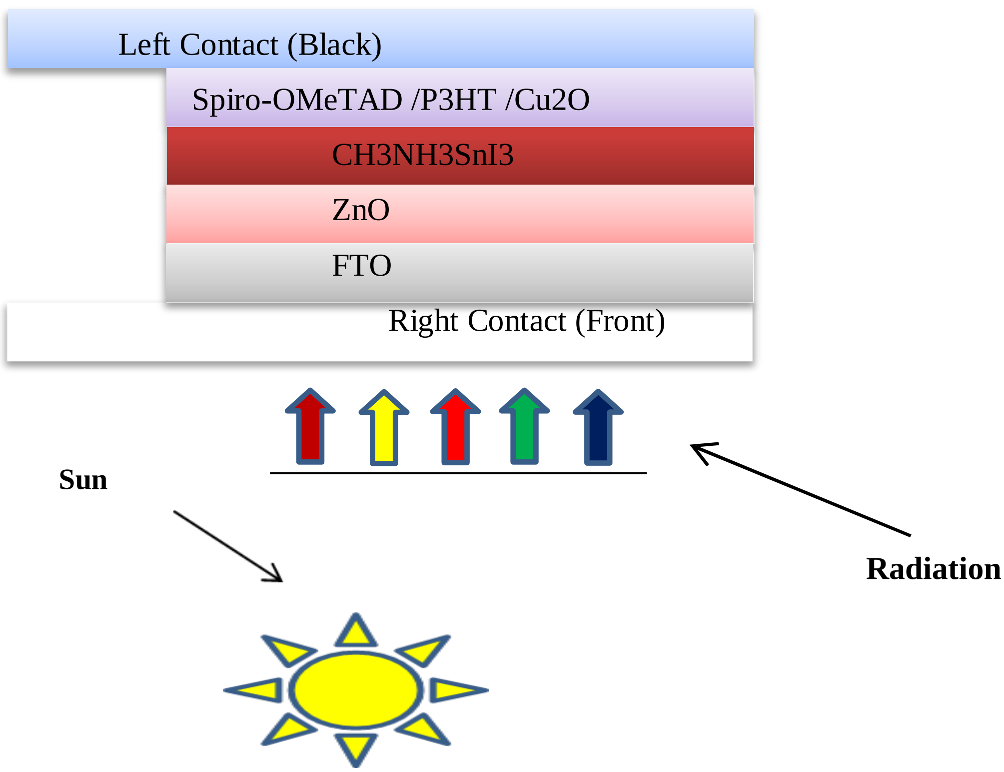

Figure 1: Schematic representation device architecture (Glass/TCO/ETL/Perovskite/HTL/Au)

b) *Parameters*

Thickness, band-gap energy, electron affinities, effective density, effective VB density, effective density, electron mobility, hole mobility, effective density, donor concentration, and acceptor concentration are among the electrical properties. It is possible to alter these electrical characteristics. The following tables provide information on the electrical parameters in the SCAPS1-D program. [14]

Table 1: Electrical Parameters of solar cells

Parameters	FTO [15]	ZnO [16]	CH3NH3SnI3 [17]	Cu2O [18]	Spiro-OMeTAD[19]	P3HT[20]
Thickness/nm	400	100	1.700	200	200	200
Band-Gap Energy E_g/ev	3.5	3.300	1.3	2.170	3.170	1.7
Electron affinity/ev	4	4	4.17	3.200	2.050	3.5
Relative permittivity er	9	9	10	10.000	3.000	3
Effective-CB density N_c/cm-3	2.2E+18	2.0E+18	1.000E+18	2.50E+20	2.200E+18	2.00E+21
Effective-VB density N_v/cm^{-3}	1.8E+19	1.8E+19	1.000E+19	2.50E+20	1.800E+19	2.00E+21
Electron Mobility un/cm2/V.s	2.00E+1	1.00E+2	1.600E+0	2.000E+2	2.000E-4	1.800E-3
Hole mobility un/cm2/V.s	1.00E+1	2.50E+1	1.600E+0	8.600E+3	2.000E-4	1.860E-2
Donar concentration N_d/cm^{-3}	2.00E+19	1.00E+18	1.000E+0	0	0	0.000E+0
Acceptor Concentration Na/cm^{-3}	0.000E+0	0.000E+0	1.000E+17	1.00E+19	12.000E+19	1.00E+18

Interface layer properties, SCAPS-1D allows users to run simulations to analyze how these properties affect device performance metrics like efficiency, open-circuit voltage, short-circuit current, and fill factor.

Table 2: Defect Parameters of interface and absorber [21]

Characteristics	HTL/Absorber	Absorber/ETL
Defect type	Neutral	Neutral
Capture cross section electrons (cm^2)	1.00E-19	1.00E-19
Capture cross section holes (cm^2)	1.00E-19	1.00E-19
Energetic distribution	Gaussian	Gaussian
Reference for defect energy level Et	Above the highest EV	Above the highest EV
Energy with respect to reference (E_v)	0.6	0.6
Total density (integrated Over all energies) (1/cm^2)	1.00E+10	1.00E+10

IV. Result Analysis

a) Impact of the Perovskite Absorbing Layer Thickness

The implementation of device's performance is significantly influenced by the absorber layer. The previously published data reveals that the photovoltaic parameters such as Jsc, Voc, The thickness of the absorber layer affects FF and PCE [22]. The thickness of the absorber layer was changed from 0.1 μm to 2.0 μm in order to obtain its portion in the device simulation. Figure 1 illustrates how the absorber layer's thickness influences the variation of photovoltaic parameters. For FTO/ZnO/CH_3NH_3SnI3/Cu_2O/Au, it has been found that Voc drops as absorber layer thickness increases.

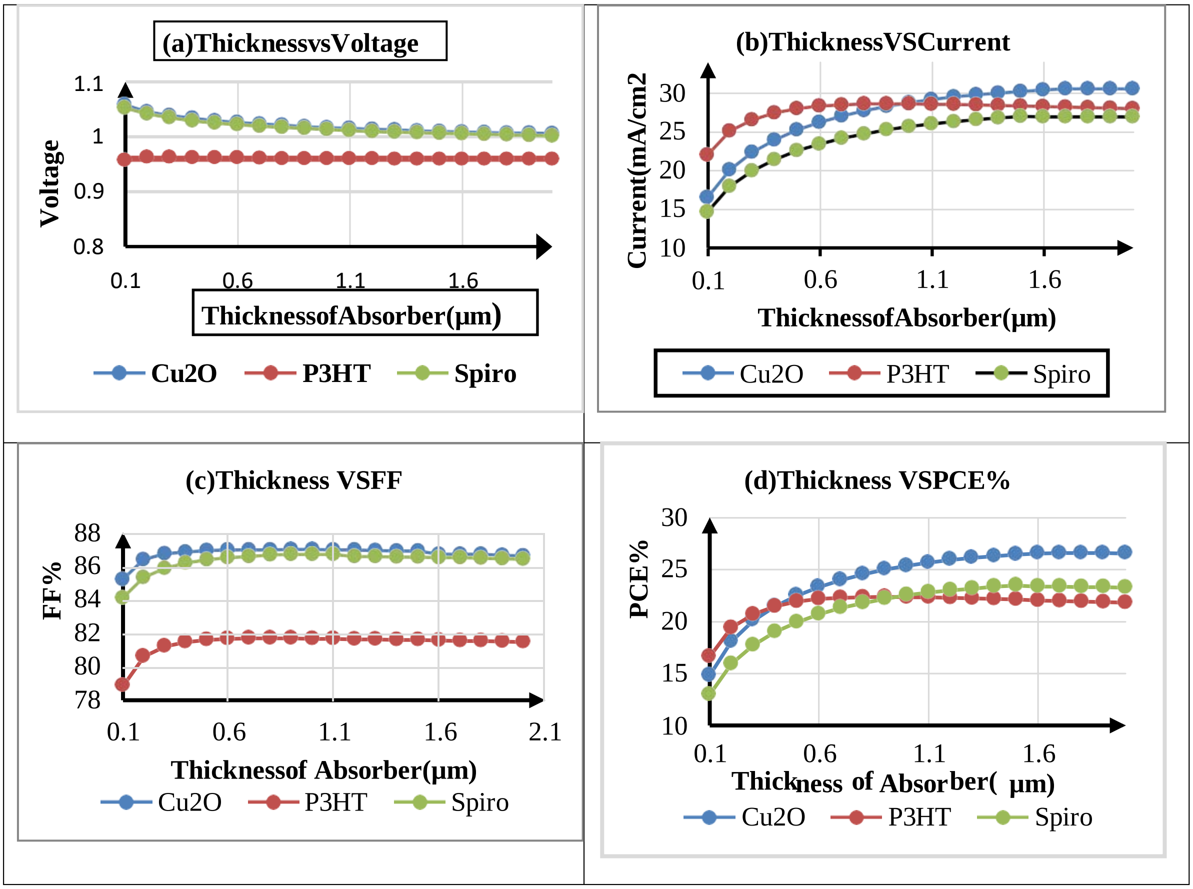

Figure 2: Variation of Solar Cell Parameters with thickness of absorber layer

V_{oc} stays constant for the FTO/ZnO/$CH_3NH_3SnI_3$/P_3HT/Au configuration, while it changes for the FTO/ZnO/$CH_3NH_3SnI_3$/Spiro-OMeTAD/Au configuration. For all devices, the current from a short circuit (J_{sc}) rises as the degree of thickness of the absorber grows. The three devices' fill factor rises to 0.3 µm before becoming saturated. For the FTO/ZnO/$CH_3NH_3SnI_3$/Cu_2O/Au Configuration, the maximum PCE is found to be 25% when the absorber layer thickness is 1.7 µm, VOC = 1V, Jsc = 31mA/cm2, and FF = 86%. Diffusion length of the absorber layer is limited, which explains why PCE decreased with adjusted thickness.

b) Effect of the Thickness Variation HTL Layer

The demonstration of a $CH_3NH_3SnI_3$ perovskite SC is also significantly impacted by the thickness of its Hole Transport (HTL) Layer. The performance of the solar cell is determined by varying the thickness of HTL between 50 and 250 nm. Voc, FF, Jsc, and PCE are seen to stay constant as HTL thickness increases.

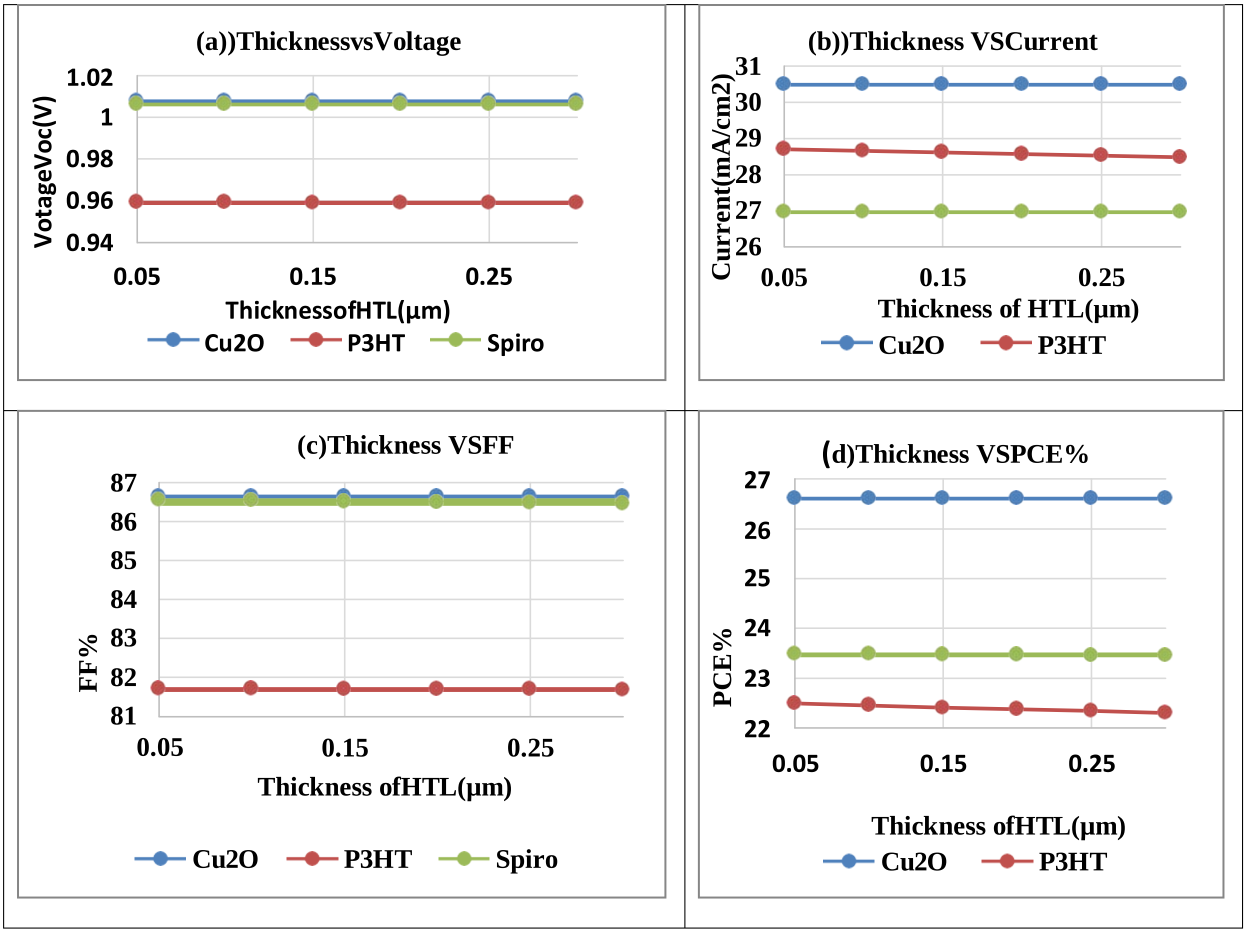

Figure 3: Changes in Solar Cell Parameters according to HTL Layer Thickness

For a variety of reasons, the solar cells' efficiency may not necessarily be greatly affected by the HTL thickness. With little recombination, HTL is intended to effectively transfer holes created in the perovskite layer to the electrode [23]. Changing the thickness of the HTL might not significantly increase charge transmission if it is already efficient in this area. It is evident from the figure that Cu_2O outperforms P_3HT and spiro-OMeTAD in terms of output. Cu_2O has a higher hole mobility than P3HT and spiro-OMeTAD, which explains why.

c) Impact of the ETL Layer's Thickness Variation

The breadth of the Electron Transport Layer (ETL) of the $CH_3NH_3SnI_3$ perovskite solar cell based can have a substantial impact on the functionality of the gadget. In this system, modification in ETL thickness can impact the $CH_3NH_3SnI_3$ perovskite solar cell. The ideal ETL thickness was determined in this study by varying the breadth of ETL between .05 µm and .15 µm. [24] It is observed that the ETL's thickness affects the solar cell's PCE and short-circuit current (J_{sc}), but not its voltage or flux (FF). With an increase in ETL thickness, Jsc and PCE both rise to 100 nm before becoming saturated. ETL is tailored to have a thickness of 100 nm.

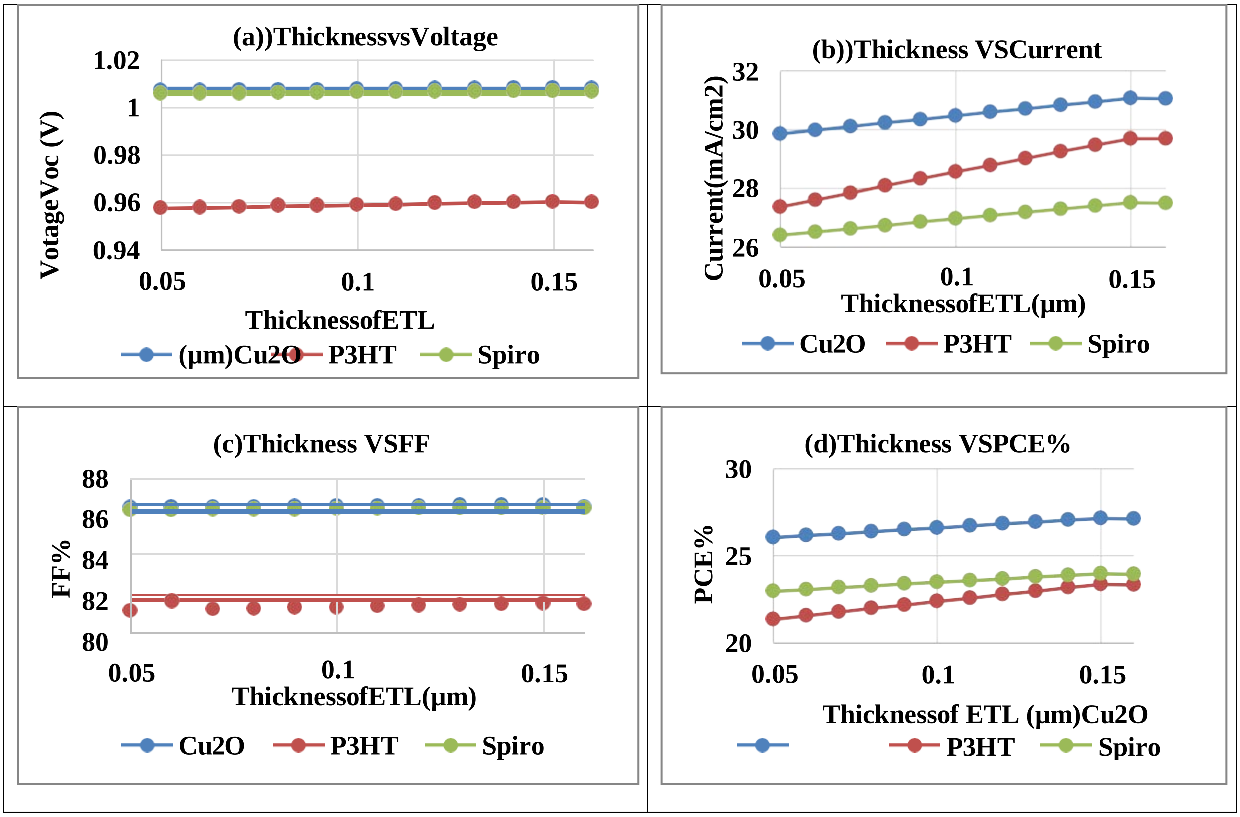

Figure 4: Changes in solar cell parameters according to ETL layer thickness

d) Impact of the Absorber Layer's Accept or Density (N_A)

Amount of doping present in the exploiter has a significant impact on photovoltaic efficiency. The response of the suggested PSC for various HTLs with variable doping densities in exploiter layer is examined in this numerical analysis. Figure 4 (a) displays the V_{OC}, J_{SC}, FF, and efficiency of the planned PSC depending on the doping of the absorber concentration. The absorber layer's doping density has been adjusted between 1×10^{13} and 1×10^{18} cm^{-3}. Up until 1×10^{15} cm^{-3}, Voc and Jsc were nearly constant; after that, Voc increased and Jsc decreased for all configurations. Furthermore, fill factor increases as absorber layer doping concentration rises. On the other hand, PCE rises to 10^{17} cm^{-3} before falling. After a given amount of doping, PCE decreases because it either produces additional defects or traps places where recombination might occur [25]. For all configurations, the absorber layer's ideal concentration of doping is 10^{17} cm^{-3}.

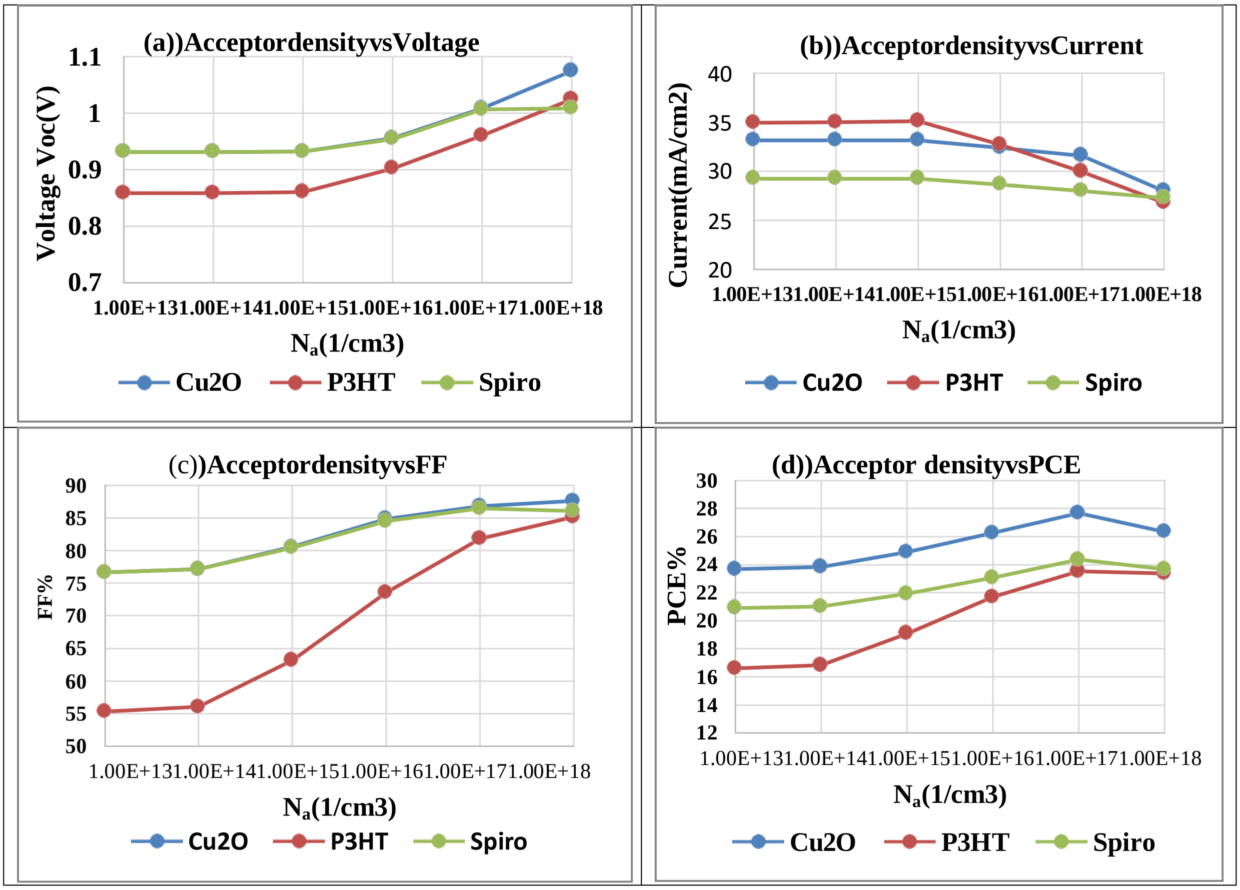

Figure 5: Variation of Solar Cell Parameters with shallow uniform acceptor density (N_A) in absorption Layer

e) Impact of Absorber Layer Defect Density (N_t) (cm^{-3})

Figure 5 depicts the fluctuation of PV characteristics in conjunction with the defect density (cm^{-3}). To achieve optimal efficiency, it is crucial to comprehend how defect densities affect device performance, as recombination and generation take place within the layer designed for absorption. The primary cause of flaws an impacted device performance is a decrease in the quality of doping levels and the technique of doping within the absorber layer. Because, perovskite layer has many different defect energy levels, the Gaussian distribution provides an ideal way to explain the absorber layer's fault densities. The relevant Gaussian distribution equations of the acceptor and donor states are as follows:

- g DE = GMd exp [2 Ad2/(E-Epkd)2]
- gAE is equal to GMa exp [(E-Epka)2/2 Ad2]

Where GMd and GMa are the real flaws densities, Ad and ΄Ea are the typical energy deviations of the acceptor and Gaussian levels, g1D € = G1 Md exp [[26].

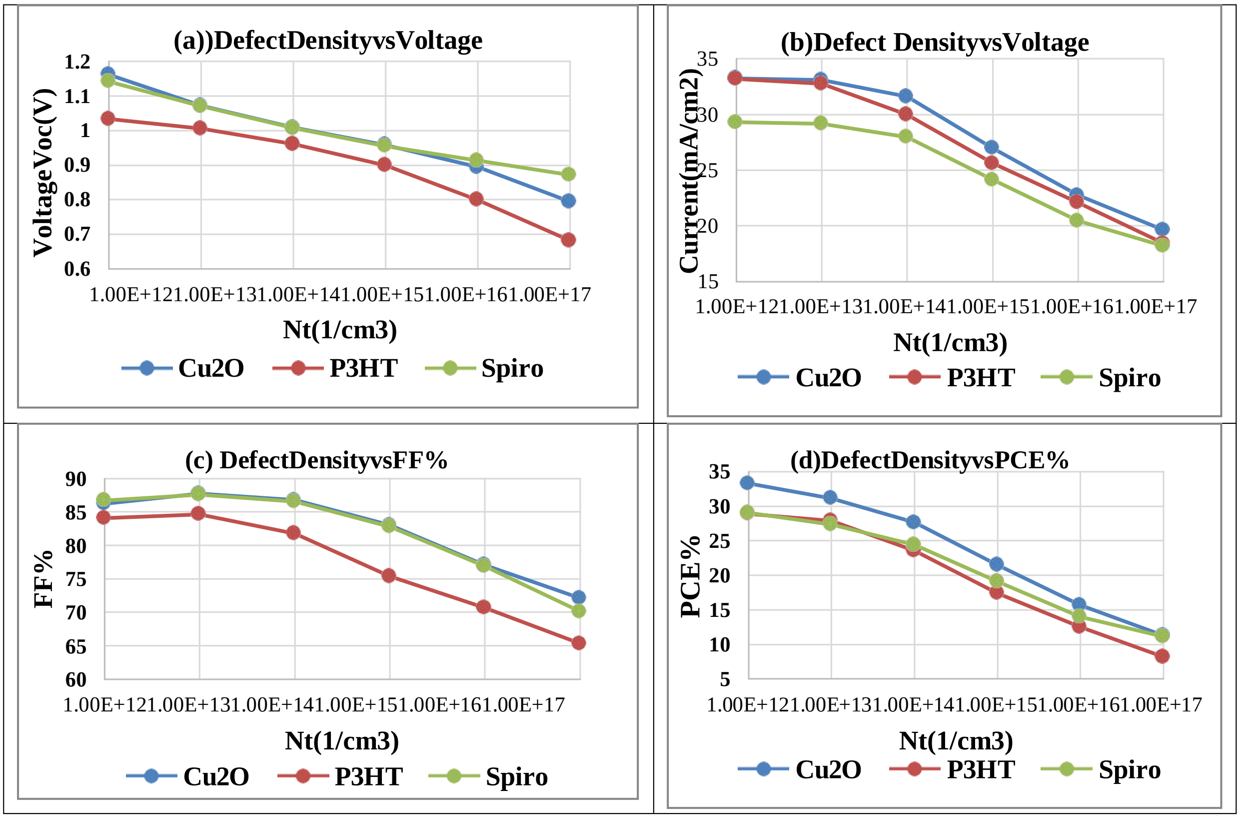

Figure 6: Changes in Solar Cell Specifications with Defect Density (N_t) (cm^{-3}) of absorber layer

The acceptor location of peak energy is obtained positively from Ev and the donor Position of peak energy is measured. positively from E_c, resulting in EPKD and Epka. Low quality perovskite layers, as shown by the plots, have a significant amount of defects densities, an elevated recombination rate of Tin (SnO_2), a decrease in the charge carriers' diffusion length, and eventually a decrease in the carriers' life duration. Above all, features have a big impact on how well the gadget performs. By altering the density of defects originating from 10^{12} cm^{-3} to 10^{17} cm^{-3}, we were able to compute the PV parameters. For Cu_2O, Spiro-OMeTAD, and P3HT, the corresponding efficiency values are 11.26%, 11.10%, and 7% if the defect density is higher than 10^{17} cm^{-3}. The model predicts that there will be a minimum of 10^{14} cm^{-3} flaws in the absorber layer.

f) Band Diagram

Understanding the QE of a perovskite PV based on $CH_3NH_3SnI_3$ requires an understanding of its band diagram. The band diagram shows how e^- and h+ flow throughout the solar cell as well as the various materials' energy levels. The band diagram for the FTO/ZnO/ $CH_3NH_3SnI_3$/Cu_2O/Au combination is displayed in Figure 6. Light will first hit the TCO, then travel through the ETL and land on the absorber layer [27]. Since ETL has a bandgap of 3.3 eV, it can absorb more sunlight. Electrons excited by photons having energies above the absorber layer's band gap, will move from the HOMO to the LUMO, leaving holes on the HOMO. Excitons or e-h pairs will result from this. The layer separating the absorber from the ETL will separate excitons. The openings will go to HTL. The charge carriers will be transported to the external circuit by two electrodes.

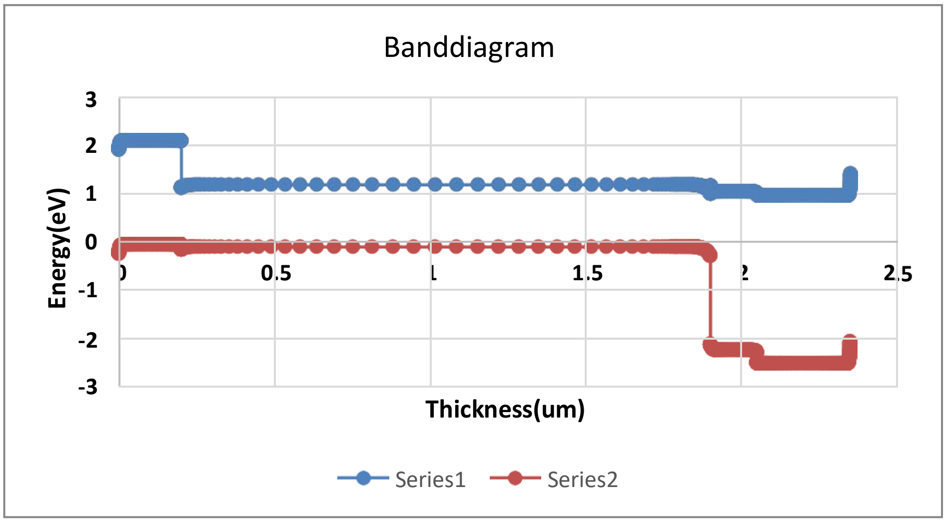

Figure 7: Band-Diagram

The band diagram illustrates the valence band and conduction band's energy levels for each material in the solar cell. It displays the perovskite layer's energy levels in the instance of $CH_3NH_3SnI_3$. For effective charge separation and collection, these energy levels must line up. Charge Generation: Electron-hole pairs, or excitons, are produced when photons are absorbed by the perovskite layer. The separation of these excitons may be seen in the band diagram, where holes stay in the VB and electrons migrate to the CB.

Carrier Transport: The band diagram shows the energy barriers and routes that electrons and holes take to move across the various layers of the solar cell. This makes it easier to understand how efficiently carriers, like as e^- and h^+, can get to the electrodes to produce the current.

g) Quantum Efficiency

The ability of a solar cell, especially perovskite solar cells, to convert incident photons into electrical current is measured by its QE. It is frequently written according to wavelength, showing the cell's effectiveness at various light wavelengths [28]. The QE spectrum sheds light on the performance of the solar cell throughout the solar spectrum.

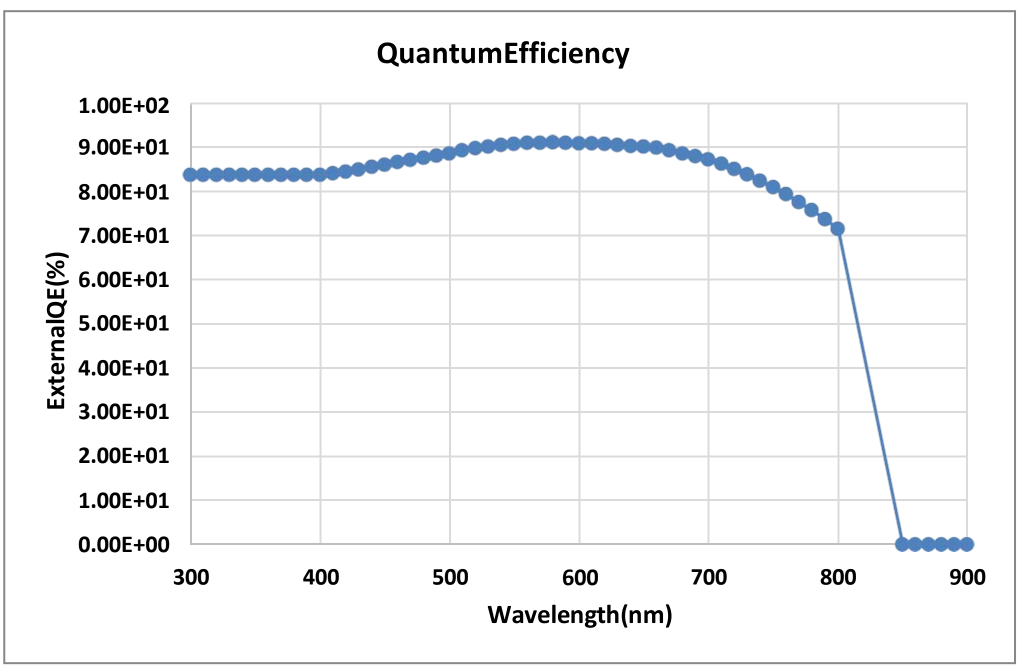

Figure 8: Quantum efficiency

In the context of solar cells, quantum efficiency (QE) is the proportion of incoming photons overall to charge carrier number (electrons or holes) produced by absorbed photons. One kind of perovskite material used in solar cells is $CH_3NH_3SnI_3$.

V. Conclusion

Using the SCAPS-1D software, a Sn-based perovskite solar cell was built and simulated for this work. Several HTLs were experimented with in this work to determine the ideal configuration. For Cu_2O, the highest efficiency was discovered. Furthermore, the absorber layer, HTL, and ETL thicknesses was adjusted to determine how the device's output changed. When the absorber layer's thicknesses, HTL, and ETL were .2 μm, .15 μm, and .17 μm correspondingly, the highest efficiency was measured. Additionally, Doping concentration and defect density in the absorber layer were adjusted, and It was found that the maximum efficiency was attained at 10^{17} cm-3 doping concentrations and 10^{14} cm-3 defect densities, respectively. Maximum power conversion efficiency of 27.66% is displayed by the optimum configuration of FTL/ZnO/$CH_3NH_3SnI_3$/Cu_2O/Au, with V_{OC} = 1.0086 V, J_{SC} = 31.59 mA/cm^2, and FF = 86.22%. The output of this lead-free organic inorganic Sn-formed PSC exhibits extremely encouraging findings, suggesting that the device can be manufactured in the future.

References Références Referencias

1. K. C. B. N. b. N. Suresh Kumar, N. and Chandra Babu Naidu, K. (2021) 'A review on perovskite solar cells (pscs), materials and applications', *Journal of Materiomics*, 7(5), pp. 940–956. doi:10.1016/j.jmat. 2021.04.002
2. J. Z. Y. Z. H. L. Q. X. X. L. Jing Wang, J. *et al.* (2020) 'Highly efficient all-inorganic perovskite solar cells with suppressed non-radiative recombination by a Lewis Base', *Nature Communications*, 11(1). doi:10. 1038/s41467-019-13909-5
3. NREL, "NREL Chart,"2018.
4. Wang, J. *et al.* (2020) 'Highly efficient all-inorganic perovskite solar cells with suppressed non-radiative recombination by a Lewis Base', *Nature Communications*, 11(1). doi:10.1038/s41467-019-13909-5
5. Himal, A. bdelkader (2018) 'GPVDM simulation of layer thickness effect on power conversion efficiency of ch3nh3pbi3 based planar heterojunction solar cell', *International Journal of Energetica*, 3(1), p. 37. doi:10.47238/ijeca.v3i1.64
6. Kojima, A. *et al.* (2009) 'Organometal halide perovskites as visible-light sensitizers for photovoltaic cells', *Journal of the American Chemical Society*, 131(17), pp. 6050–6051. doi:10. 1021/ja809598r
7. Im, J.-H. *et al.* (2011)'6.5% efficient perovskite quantum-dot-sensitized solar cell', *Nanoscale*, 3(10), p. 4088. doi:10.1039/c1nr10867k
8. Green, M.A., Ho-Baillie, A. and Snaith, H.J. (2014) 'The emergence of perovskite solar cells'', *Nature Photonics*' 8(7), pp. 506–514. doi:10.1038/nphoton. 2014.134
9. Conings, B. *et al.* (2014) 'An easy-to-fabricate low-temperature tio2 electron collection layer for high efficiency planar heterojunction perovskite solar cells', *APL Materials*, 2(8). doi:10.1063/1.4890245
10. Peplow, M. (2014) 'The Perovskite Revolution [News]', *IEEE Spectrum*, 51(7), pp. 16–17. doi:10. 1109/mspec.2014.6840788
11. M. Burgelman, P. Nollet, S. Degrave, Modelling polycrystalline semiconductor solar cells, Thin Solid Films, 361 (2000) 527-532.
12. M. Burgelman, K. Decock, S. Khelifi and A. Abass, Advanced electrical stimulation of thin film solar cells, Thin Solid Films, 535 (2013) 296-301.
13. Kanoun, A.-A.; Kanoun, M.B.; Merad, A.E.; Goumri-Said, S. Toward development of high-performance perovskite solar cells based on CH3NH3GeI3 using computational approach. Sol. Energy 2019, 182, 237–244.
14. Hao, L.; Zhou, M.; Song, Y.; Ma, X.; Wu, J.; Zhu, Q.; Fu, Z.; Liu, Y.; Hou, G.; Li, T. Tin-based perovskite solar cells: Further improve the performance of the electron transport layer-free structure by device simulation. Sol. Energy 2021, 230, 345–354.
15. Deepthi Jayan, K.; Sebastian, V. Comprehensive device modelling and performance analysis of MASnI3 based perovskite solar cells with diverse ETM, HTM and back metal contacts. Sol. Energy 2021, 217, 40–48.
16. Ito, N.; Kamarudin, M.A.; Hirotani, D.; Zhang, Y.; Shen, Q.; Ogomi, Y.; Iikubo, S.; Minemoto, T.; Yoshino, K.; Hayase, S. Mixed Sn–Ge perovskite for enhanced perovskite solar cell performance in air. J. Phys. Chem. Lett. 2018, 9, 1682–1688.
17. S. Z. Haider, H. Anwar and M. Anwar, "A comprehensive device modelling of perovskite solar cell with inorganic copper iodide as hole transport material semiconductor," Science Advanced, vol. 5, no. 8, p. 33-34, 2018.
18. Sunny, A. et al. (2021), Numerical study of high performance HTL-free CH3NH3SnI3-based perovskite solar cell by SCAPS-1D'', AIP Advances, 11(6). doi:10.1063/5.0049646
19. Omarova, Z. et al. (2022), In silico investigation of the impact of Hole-transport layers on the performance of CH3NH3SnI3 perovskite photovoltaic cells'', Crystals, 12(5), p. 699. doi:10. 3390/cryst12050699
20. Fatema, K. and Arefin, M.S. (2022), Enhancing the efficiency of PB-based and sn-based perovskite solar cell by applying different ETL and HTL using

Global Journal of Research in Engineering (F) XXIV Issue I Version I Year 2024

SCAPS-ID‟, Optical Materials, 125, p. 112036. doi:10.1016/j.optmat.2022.112036

21. Shamna, M.S., Nithya, K.S. and Sudheer, K.S. (2020), Simulation and optimization of CH3NH3SNI3 based inverted perovskite solar cell with NIO as hole transport material‟, Materials Today: Proceedings, 33, pp. 1246–1251. doi:10.1016/j.matpr.2020.03.488
22. Y.H. Khattak, F. Baig, S. Ullah, B. Marí, S. Beg, and K. Khan, Effect of Cu2O hole transport layer and improved minority carrier lifetime on the efficiency enhancement of CH3NH3SnI3 based experimental solar cell. J. Renew. Sustain. Energy 10, 043502 (2018). https://doi.org/10.1063/1.5037471
23. Fatema, K. and Arefin, M.S. (2022), Enhancing the efficiency of PB-based and sn-based perovskite solar cell by applying different ETL and HTL using SCAPS-ID‟, Optical Materials, 125, p. 112036. doi:10.1016/j.optmat.2022.112036
24. M. Burgelman, J. Marlein, Analysis of graded band gap solar cells with SCAPS, proceedings of the 23rd European Photovoltaic Solar Energy Conference, Valencia, 2008, pp. 2151-2155.
25. J. P. Mailoa, C. D. Bailie, E. C. Johlin, E. T. Hoke, A. J. Akey, W. H. Nguyen, M.D. McGhehee and T. Buonassisi, “A 2-terminal perovskite/silicon multi-junction solar cell enable by a silicon tunnel junction,” Applied Physics Letters,vol. 106, no. 12, 2015.
26. S. Albrecht, M. Saliba, J. P. Correa Baena, F. Lang, L. Kegelmann, M. Mews, L. Steier, A Abate, J. Rappich, L. Korte, R. Schlatmann, M. K. Nazeeruddin, A Hagfeldt, M. Gratzel and Re, “Monolithic perovskite/silicon-heterojunction tandem solar cell processed at low temperature,” Energy Environment and Science, vol. 9, no. 1, p. 81-88, 2016.
27. J. Werner, C.-H. Weng, A. Walter, L. Fesquet, J. P. Seif, S. De Wolf, D. Niesen and C. Ballif, “Efficient Monolithic Perovskite/Silicon Tandem Solar Cell with Cell Area>1cm,” The Journal of Physics Chemistry Letters, vol. 7, no. 1, p. 161-166, 2015.

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Fault Current Limiters: Enhancing Power System Stability and Safety

By Sanjay Koul
Gulbarga University

Abstract- This paper presents the overview of Fault Current Limiters, its evolution with timeline, types and alternate options. The study can help the user give more insight to various types and alternate options for selection of fault current limiter. The paper reveals that FCL is crucial for limiting fault current and enhancing power system stability, reliability and safety.

Keywords: *fault current limiters, resistive FCL, inductive FCL, superconducting FCL, solid state FCL, hybrid FCL, power system stability.*

GJRE-F Classification: *LCC Code: TK3228*

Fault Current Limiters: Enhancing Power System Stability and Safety

Sanjay Koul

Abstract- This paper presents the overview of Fault Current Limiters, its evolution with timeline, types and alternate options. The study can help the user give more insight to various types and alternate options for selection of fault current limiter. The paper reveals that FCL is crucial for limiting fault current and enhancing power system stability, reliability and safety.

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I. Introduction

In the early days of electricity distribution, fault currents were not a major concern because the electrical networks were relatively small and the generation capacities were limited. The traditional protection devices such as fuses and circuit breakers were used to manage fault conditions. These devices were adequate for the smaller grids of the time but were not designed to handle the high fault currents that would come with the growth of larger interconnected grids.

As electrical grids expanded and the demand for energy grew, the size and complexity of power networks grew significantly which resulted in the need for a more reliable and effective method to manage and control fault currents became evident.

To address the growing challenge of managing fault currents, Fault Current Limiters (FCLs) emerged as a vital technology to address increasing fault current levels in modern power systems. FCLs were developed to provide a solution that would protect critical infrastructure and improve the safety and reliability of power distribution networks and enabling the use of equipment with lower interrupting ratings. FCLs limit the peak fault current that could occur during a fault event, reducing the stress on system components and preventing potential damage.

Fault Current Limiters have evolved from early 20^{th} century to present times, transitioning from traditional circuit breakers and fuses to sophisticated devices that utilize superconducting materials, solid state and hybrid technology.

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Basic Principle of How Fault Current Limiters Work:

Normal Operation: Under normal conditions, FCLs have very low impedance and do not significantly affect the operation of the power system.

Fault Condition: When a fault (e.g., short circuit, overload) occurs, the FCL quickly increases its impedance. This limits the magnitude of the fault current, protecting downstream equipment.

Post-Fault Recovery: After the fault is cleared, the FCL typically returns to its low-impedance state, restoring normal operation.

II. Evolution with Timeline

The evolution of Fault Current Limiters (FCLs) has been marked by technological advancements aimed at improving power system protection and management of fault currents. Here's a timeline outlining key milestones in the development of FCLs:

Early 20th Century: Current Limiting Fuses:

1900s: Current Limiting Fuses became the first widely used devices to limit fault current in power systems. They worked by melting under high current conditions to interrupt the circuit, providing simple and cost-effective protection.

1920s–1950s: Use of Circuit Breakers and Reactors:

1920s: Air Circuit Breakers (ACBs) and oil circuit breakers became popular as power systems expanded. They provided fault interruption but didn't limit the fault current, leading to the search for better solutions.

1930s: Series Reactors began to be used to limit fault current by adding impedance to the circuit, though they caused voltage drops and energy losses.

1950s: The development of vacuum and SF6 circuit breakers improved the ability to handle higher fault currents but didn't limit fault magnitude.

1960s: Introduction of Resistive Fault Current Limiters:

1960s: The first Resistive Fault Current Limiters (R-FCLs) were developed to reduce fault currents by adding resistance during fault conditions. These devices, however, faced challenges with heat dissipation and size.

1970s: Growth of Power Systems and Emerging Fault Limitation Needs:

1970s: With the rapid expansion of electrical grids, particularly in industrialized nations, fault current levels increased significantly. This spurred interest in more advanced methods of fault current limitation.

1970s: Current Limiting Reactors gained more use, but their drawbacks (e.g., voltage drop during normal operation and power loss) led to further research into alternatives.

1980s: Early Development of Superconducting Fault Current Limiters (SFCLs):

1980s: The concept of Superconducting Fault Current Limiters (SFCLs) was introduced. These devices offered high current-limiting potential with low impedance during normal operation. The challenge, however, was the need for cryogenic cooling systems, making them costly and complex.

1990s: Practical Prototypes of SFCLs and Hybrid FCLs:

1990s: Advancements in high-temperature superconductors (HTS) made SFCLs more feasible, though they were still largely in the prototype stage. The potential of superconductors to limit fault current with little to no loss during normal operation garnered significant interest.

1990s: Hybrid Fault Current Limiters that combined resistive elements with other technologies began to emerge. These offered more efficient solutions with better cost-effectiveness compared to purely resistive or superconducting options.

2000s: Commercialization of Advanced Fault Current Limiters:

Early 2000s: Commercialization of resistive FCLs and early SFCL products began, particularly in high-power industrial and grid applications. These devices were still expensive but proved effective in limiting fault currents in critical systems.

2003: The first Superconducting FCL was successfully installed in a medium-voltage grid in Europe, marking a significant milestone in the application of SFCLs in practical power systems.

Mid-2000s: Hybrid FCLs became more refined, combining various elements like resistance, inductance, and even solid-state devices to improve fault current limiting in a more cost-efficient manner.

2010s: Expansion of FCL Applications and Further SFCL Development:

2010s: Increased deployment of SFCLs in medium and high-voltage applications, particularly in Europe, Japan, and the U.S., where the need to limit fault current in expanding grids became critical.

2012: An SFCL was installed in Germany in a 10kV grid, which became a showcase for the future of fault current limitation in smart grids.

2015: Solid-State FCLs (SSFCLs) using semiconductor technology began to be developed. These devices promised ultra-fast response times and were aimed at smart grids and renewable energy systems, where fault current control is more critical.

2020s: Focus on Smart Grids and Renewable Integration:

2020s: With the global push toward renewable energy and smart grid technologies, the demand for advanced FCLs increased. The need for fault current limitation became particularly relevant in renewable energy systems where the variability of power sources can lead to challenging fault conditions.

2021–Present: SFCLs continue to advance with improvements in cooling technology, making them more feasible for broader adoption. Hybrid and Solid-State FCLs are gaining attention for their faster response times, smaller sizes, and ability to handle fault conditions in modern grids.

III. Types and Comparison

There are different types of FCLs, including resistive, inductive, superconducting, and non-superconducting varieties. The superconducting fault current limiters (SFCLs) are especially notable for their low impedance during normal operation, but rapidly switch to high impedance during fault conditions, minimizing the impact of high fault currents. Non-superconducting FCLs, like reactors or solid-state devices, also play significant roles in limiting short-circuit currents, but often with trade-offs in efficiency or response time.

a) Superconducting Fault Current Limiter (SFCL)

Working Principle- SFCLs use superconducting materials, which exhibit zero resistance and negligible impedance under normal conditions. It exploit the extremely rapid loss of superconductivity (called "quenching") above a critical combination of temperature, current density, and magnetic field.

When a fault occurs, the superconductor quenches, its resistance rises sharply and current is diverted to a parallel circuit with the desired higher impedance, limiting the fault current.

Types- Resistive SFCLs: The superconducting material itself limits the current and Inductive SFCLs: Superconductors are used in an inductive coupling arrangement.

Advantages- Very fast response time (within milliseconds), High current-limiting capability and Minimal losses under normal conditions

Disadvantages- High cost due to the need for cryogenic cooling systems to maintain the superconducting state and Complex maintenance.

Applications- Widely used in high-voltage grids, especially in substations and transmission networks, Systems with very high fault currents, often used in critical infrastructure where downtime is not an option and Low impedance during normal operation, very effective at limiting high fault currents.

Cost: High- SFCLs are among the most expensive types of FCLs due to the cost of high-temperature superconducting (HTS) materials and the cryogenic cooling systems required.

b) Resistive Fault Current Limiter (RFCL)

Working Principle: In a RFCL, the current passes directly through the superconductor. When it quenches, the sharp rise in resistance reduces the fault current from what it would otherwise be (the prospective fault current). A resistive FCL can be either DC or AC. If it is AC, then there will be a steady power dissipation from AC losses (superconducting hysteresis losses) which must be removed by the cryogenic system. An AC FCL is usually made from wire wound non-inductively; otherwise the inductance of the device would create an extra constant power loss on the system.

Advantages- Simple design and relatively low cost, Easy to install, lower maintenance and No need for cryogenic cooling or complex components.

Disadvantages- Causes power losses due to the introduction of resistance, Limited current-limiting capability compared to SFCLs and Generates heat during operation, which may require cooling systems.

Applications- Suitable for low to medium voltage systems where high performance isn't critical and Suitable for systems that require moderate fault current limitation with a lower budget.

Cost: Low to Medium- Typically, resistive FCLs are among the more affordable types, with lower upfront and maintenance costs compared to more complex systems.

c) Inductive Fault Current Limiter (IFCL)

Working Principle: Inductive FCLs come in many variants, but the basic concept is a transformer with a resistive FCL as the secondary. In normal operation, there is no resistance in the secondary and so the inductance of the device is low. A fault current quenches the superconductor, the secondary becomes resistive and the inductance of the whole device rises. The advantage of this design is that there is no heat ingress through current leads into the superconductor, and so the cryogenic power load may be lower. However, the large amount of iron required means that inductive FCLs are much bigger and heavier than resistive FCLs.

The quench process is a two-step process. First, a small region quenches directly in response to a high current density. This section rapidly heats by Joule heating, and the increase in temperature quenches adjacent regions.

Advantages- Reliable, robust design and can handle continuous operation and No need for external power or cooling.

Disadvantages- Slower response time compared to other FCL types, Causes voltage drops and power losses during normal operation, large footprint and Bulky design, requiring more space.

Applications- Mainly used in industrial systems, substations, or high-power equipment, Often used in high-current industrial applications or substations where fault current is high, but cost is still a concern.

Cost: Medium- Series reactors are somewhat more expensive than resistive FCLs due to the need for heavy-duty materials like copper or aluminum windings and insulation.

d) Solid-State Fault Current Limiter (SSFCL)

Working Principle: SSFCLs use power electronic devices (like thyristors or insulated-gate bipolar transistors, IGBTs) to limit the current. These devices control the flow of electricity electronically and can react very quickly to faults.

Advantages- Very fast response time (within microseconds), No moving parts, minimal maintenance, High flexibility, control and Can handle large fault currents.

Disadvantages- Expensive due to semiconductor components, complex to design and integrate and Power losses during operation.

Applications- Used in modern grids, smart grids, and systems where fast response to faults is critical (e.g., renewable energy systems).

Cost: Medium to High- Solid-state FCLs use semiconductor technology, which makes them faster but also more expensive compared to traditional resistive or inductive FCLs.

e) Hybrid Fault Current Limiter (HFCL)

Working Principle: Hybrid FCLs combine two or more FCL technologies (e.g., superconducting and resistive, or superconducting and solid-state) to create a more effective current-limiting solution.

Advantages- Combines the benefits of different technologies (e.g., fast response time and low losses), Greater fault-handling capability and Provides a good compromise between cost, performance, and complexity.

Disadvantages- Higher cost and complexity compared to single-type FCLs and More complex than single-technology FCLs, potentially higher maintenance costs and challenges.

Global Journal of Research in Engineering (F) XXIV Issue I Version I Year 2024

Applications- Used in high-voltage grids where more sophisticated solutions are needed and Used in systems that need a flexible, adaptable approach to fault current limitation without the full cost of SFCLs.

Cost: Medium to High- Hybrid FCLs combine elements of resistive, inductive, or superconducting technologies, offering a balance between performance and cost.

f) Summary of Technical Comparison

Table 1

Parameter	Resistive FCL (RFCL)	Inductive FCL (IFCL)	Superconducting FCL (SFCL)	Solid-State FCL (SSFCL)	Hybrid FCL (Saturable Core)
Fault Response Speed	Medium	Slow	Fast	Very fast	Fast
Energy Loss in Normal Operation	Moderate	Moderate	Very low (zero resistance)	Moderate to high	Very low (saturated core)
Footprint/Size	Large	Large	Compact	Compact	Medium
Cost	Moderate	Low	High (superconductors + cooling)	High (power electronics)	Moderate
Complexity	Low	Low	High (cooling systems required)	High (control systems)	Moderate
Maintenance	Low to moderate	Low	High (due to cooling systems)	Moderate to high (complex systems)	Moderate
Operational Temperature	Room temperature	Room temperature	Cryogenic cooling required	Room temperature	Room temperature
Applications	Industrial, distribution grids	Transmission, distribution grids	High-voltage grids, renewable systems	Industrial, smart grids, renewables	Transmission, smart grids, renewables
Advantages	Low cost, simple design	Reliable, can handle high currents	Low impedance, very effective at high fault currents	Fast response, no moving parts	Balances cost and performance
Disadvantages	Heat generation, limited to moderate applications	Voltage drop, large size, and weight	Very expensive, requires cryogenic cooling	High cost due to semiconductor technology	More complex, potentially higher maintenance

Low-budget systems: Resistive FCLs or Inductive FCLs are generally preferred.

High-performance systems: SFCLs and Solid-State FCLs are suited but are significantly more expensive.

Medium-budget or versatile systems: Hybrid FCLs offer a good balance between cost and performance.

IV. Alternatives Options

Some of the alternative options are as described below:

a) Current-Limiting Reactors

How It Works: Reactors are inductive elements placed in series with the electrical network to introduce additional impedance during fault conditions, thereby limiting the fault current.

Advantages: Simple and cost-effective; reactors are widely used in transmission and distribution systems.

Drawbacks: Reactors increase impedance during normal operation, leading to voltage drops and power losses. They may also require significant space.

b) Current-Limiting Fuses

How It Works: Current-limiting fuses interrupt fault currents by melting when the current exceeds a certain threshold. These fuses are commonly used in medium- and low-voltage systems.

Advantages: Cost-effective, reliable, and compact; they operate quickly during fault conditions.

Drawbacks: Fuses need to be replaced after operation, which can lead to downtime. They are not reusable and are less suited for high-current, high-voltage applications.

c) High-Impedance Transformers

How It Works: Transformers with higher impedance inherently limit the current flowing through them, thus reducing fault current levels downstream.

Advantages: Passive and reliable; commonly used in distribution systems.

Drawbacks: High impedance can lead to voltage regulation issues and losses during normal operation.

d) Splitting the System into Smaller Sections

How It Works: By dividing the network into smaller sections or zones, fault currents can be reduced in any one part of the system. This method is often paired with advanced protection schemes to isolate faults quickly.

Advantages: Helps to manage fault levels by reducing the overall capacity of each section.

Drawbacks: This solution may require additional circuit breakers and protection devices, increasing costs and complexity.

e) Reducing Short-Circuit Levels by Network Reconfiguration

How It Works: Changing the topology of the network (e.g., by opening or closing switches) can reduce the fault level in certain parts of the system. For example, closing a normally open tie switch can reroute power and reduce the impact of a fault in another part of the system.

Advantages: Dynamic and flexible; allows for adaptive fault current management without new equipment.

Drawbacks: Requires advanced control systems and may lead to load imbalances or other operational issues.

f) Digital Protection Relays with Advanced Coordination

How It Works: Modern digital relays can be programmed to respond dynamically to fault conditions, adjusting the protection settings based on the location and severity of the fault. They can also coordinate with other protection devices to limit the fault current impact.

Advantages: Flexible, and can improve system resilience.

Drawbacks: Requires advanced control systems and careful coordination of protection settings.

g) Fault-Tolerant Equipment Design

How It Works: Upgrading the design of critical equipment (e.g., cables, transformers, switchgear) to withstand higher fault currents can eliminate the need for current-limiting devices.

Advantages: Increases the fault tolerance of the system, potentially reducing the need for active fault management.

Drawbacks: Can be costly and requires careful design to ensure fault currents do not exceed equipment ratings.

While FCLs are highly effective in limiting fault current, other methods such as current-limiting reactors, reconfiguring the network, or upgrading equipment can achieve similar results, depending on the specific needs and limitations of the electrical system. The best approach often involves a combination of methods based on a detailed fault analysis, economic considerations, and operational flexibility.

V. Conclusion

Fault Current Limiters have in last few decades found increasing attention than before due to increase in size and complexity of modern power network systems as a result of higher energy demand. FCLs are implemented in power generation, transmission, and distribution systems to enhance grid stability, reliability, safety and enable the use of equipment with lower interrupting ratings. FCLs limit the peak fault current that could occur during a fault event, reducing the stress on system components and preventing potential damage.

References Références Referencias

1. Impact of Fault Current Limiters on Power System Protection - Electric Power Systems Research, T. R. Smith, M. A. Smith, 2020.
2. Evaluation of Hybrid Fault Current Limiter Performance in Electrical Grids - Energy Reports, L. K. Lee, H. A. Williams, 2023.
3. Solid-State Fault Current Limiters: Technological Developments and Applications - Journal of Electrical Engineering & Technology, R. H. Lee, J. Y. Choi, 2021.
4. Analysis of Fault Current Limiter Impact on Distribution Networks - Electric Power Systems Research, H. C. Patel, R. M. Roy, 2021.
5. Comparative Study of Fault Current Limiter Technologies - Energy Conversion and Management, J. L. Williams, M. K. Reddy, 2022.
6. Hybrid Fault Current Limiter Performance in Smart Grids - Smart Grid, M. K. Tsoi, A. P. Smith, 2023.
7. Fault Current Limiting Devices for Urban Power Grids - Electric Power Research Institute Journal, K. W. Sun, P. B. Lee, 2022.
8. Application of Fault Current Limiters in Industrial Power Systems - Industrial Engineering Journal, L. C. Thomas, D. M. Peterson, 2021.
9. Fault Current Limiter Impact on System Reliability - International Journal of Electrical Power & Energy Systems, K. R. White, M. J. Green, 2020.
10. Reliability and Performance of Fault Current Limiting Technologies - Energy Reports, N. A. Patel, L. D. Matthews, 2021.
11. The Role of Fault Current Limiters in Modern Power Grids - Journal of Energy Resources Technology, P. K. Walker, M. A. Taylor, 2022.
12. Fault Current Limiter Integration in High Voltage Networks - IEEE Transactions on Power Delivery, S. A. Lewis, T. B. Lee, 2022.
13. Economic Impact of Fault Current Limiters in Electrical Networks - International Journal of Electrical Power & Energy Systems, C. P. Richards, D. E. Harris, 2021.
14. Solid-State Fault Current Limiters: Emerging Trends and Applications - Journal of Power Electronics, N. S. Wong, J. T. Smith, 2022.

15. Hybrid Fault Current Limiter Design for Smart Grid Applications - IEEE Transactions on Smart Grid, T. E. Fisher, H. D. Turner, 2023.
16. Impact of Fault Current Limiters on Grid Stability and Reliability - International Journal of Electrical Power & Energy Systems, J. P. Carter, D. M. Allen, 2022.

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9. Produce good diagrams of your own: Always try to include good charts or diagrams in your paper to improve quality. Using several unnecessary diagrams will degrade the quality of your paper by creating a hodgepodge. So always try to include diagrams which were made by you to improve the readability of your paper. Use of direct quotes: When you do research relevant to literature, history, or current affairs, then use of quotes becomes essential, but if the study is relevant to science, use of quotes is not preferable.

10. Use proper verb tense: Use proper verb tenses in your paper. Use past tense to present those events that have happened. Use present tense to indicate events that are going on. Use future tense to indicate events that will happen in the future. Use of wrong tenses will confuse the evaluator. Avoid sentences that are incomplete.

11. Pick a good study spot: Always try to pick a spot for your research which is quiet. Not every spot is good for studying.

12. Know what you know: Always try to know what you know by making objectives, otherwise you will be confused and unable to achieve your target.

13. Use good grammar: Always use good grammar and words that will have a positive impact on the evaluator; use of good vocabulary does not mean using tough words which the evaluator has to find in a dictionary. Do not fragment sentences. Eliminate one-word sentences. Do not ever use a big word when a smaller one would suffice.

Verbs have to be in agreement with their subjects. In a research paper, do not start sentences with conjunctions or finish them with prepositions. When writing formally, it is advisable to never split an infinitive because someone will (wrongly) complain. Avoid clichés like a disease. Always shun irritating alliteration. Use language which is simple and straightforward. Put together a neat summary.

14. Arrangement of information: Each section of the main body should start with an opening sentence, and there should be a changeover at the end of the section. Give only valid and powerful arguments for your topic. You may also maintain your arguments with records.

15. Never start at the last minute: Always allow enough time for research work. Leaving everything to the last minute will degrade your paper and spoil your work.

16. Multitasking in research is not good: Doing several things at the same time is a bad habit in the case of research activity. Research is an area where everything has a particular time slot. Divide your research work into parts, and do a particular part in a particular time slot.

17. Never copy others' work: Never copy others' work and give it your name because if the evaluator has seen it anywhere, you will be in trouble. Take proper rest and food: No matter how many hours you spend on your research activity, if you are not taking care of your health, then all your efforts will have been in vain. For quality research, take proper rest and food.

18. Go to seminars: Attend seminars if the topic is relevant to your research area. Utilize all your resources.

19. Refresh your mind after intervals: Try to give your mind a rest by listening to soft music or sleeping in intervals. This will also improve your memory. Acquire colleagues: Always try to acquire colleagues. No matter how sharp you are, if you acquire colleagues, they can give you ideas which will be helpful to your research.

20. Think technically: Always think technically. If anything happens, search for its reasons, benefits, and demerits. Think and then print: When you go to print your paper, check that tables are not split, headings are not detached from their descriptions, and page sequence is maintained.

21. Adding unnecessary information: Do not add unnecessary information like "I have used MS Excel to draw graphs." Irrelevant and inappropriate material is superfluous. Foreign terminology and phrases are not apropos. One should never take a broad view. Analogy is like feathers on a snake. Use words properly, regardless of how others use them. Remove quotations. Puns are for kids, not grunt readers. Never oversimplify: When adding material to your research paper, never go for oversimplification; this will definitely irritate the evaluator. Be specific. Never use rhythmic redundancies. Contractions shouldn't be used in a research paper. Comparisons are as terrible as clichés. Give up ampersands, abbreviations, and so on. Remove commas that are not necessary. Parenthetical words should be between brackets or commas. Understatement is always the best way to put forward earth-shaking thoughts. Give a detailed literary review.
22. Report concluded results: Use concluded results. From raw data, filter the results, and then conclude your studies based on measurements and observations taken. An appropriate number of decimal places should be used. Parenthetical remarks are prohibited here. Proofread carefully at the final stage. At the end, give an outline to your arguments. Spot perspectives of further study of the subject. Justify your conclusion at the bottom sufficiently, which will probably include examples.
23. Upon conclusion: Once you have concluded your research, the next most important step is to present your findings. Presentation is extremely important as it is the definite medium though which your research is going to be in print for the rest of the crowd. Care should be taken to categorize your thoughts well and present them in a logical and neat manner. A good quality research paper format is essential because it serves to highlight your research paper and bring to light all necessary aspects of your research.

Informal Guidelines of Research Paper Writing

Key points to remember:

- Submit all work in its final form.
- Write your paper in the form which is presented in the guidelines using the template.
- Please note the criteria peer reviewers will use for grading the final paper.

Final points:

One purpose of organizing a research paper is to let people interpret your efforts selectively. The journal requires the following sections, submitted in the order listed, with each section starting on a new page:

The introduction: This will be compiled from reference matter and reflect the design processes or outline of basis that directed you to make a study. As you carry out the process of study, the method and process section will be constructed like that. The results segment will show related statistics in nearly sequential order and direct reviewers to similar intellectual paths throughout the data that you gathered to carry out your study.

The discussion section:

This will provide understanding of the data and projections as to the implications of the results. The use of good quality references throughout the paper will give the effort trustworthiness by representing an alertness to prior workings.

Writing a research paper is not an easy job, no matter how trouble-free the actual research or concept. Practice, excellent preparation, and controlled record-keeping are the only means to make straightforward progression.

General style:

Specific editorial column necessities for compliance of a manuscript will always take over from directions in these general guidelines.

To make a paper clear: Adhere to recommended page limits.

Mistakes to avoid:

- Insertion of a title at the foot of a page with subsequent text on the next page.
- Separating a table, chart, or figure—confine each to a single page.
- Submitting a manuscript with pages out of sequence.
- In every section of your document, use standard writing style, including articles ("a" and "the").
- Keep paying attention to the topic of the paper.

- Use paragraphs to split each significant point (excluding the abstract).
- Align the primary line of each section.
- Present your points in sound order.
- Use present tense to report well-accepted matters.
- Use past tense to describe specific results.
- Do not use familiar wording; don't address the reviewer directly. Don't use slang or superlatives.
- Avoid use of extra pictures—include only those figures essential to presenting results.

Title page:

Choose a revealing title. It should be short and include the name(s) and address(es) of all authors. It should not have acronyms or abbreviations or exceed two printed lines.

Abstract: This summary should be two hundred words or less. It should clearly and briefly explain the key findings reported in the manuscript and must have precise statistics. It should not have acronyms or abbreviations. It should be logical in itself. Do not cite references at this point.

An abstract is a brief, distinct paragraph summary of finished work or work in development. In a minute or less, a reviewer can be taught the foundation behind the study, common approaches to the problem, relevant results, and significant conclusions or new questions.

Write your summary when your paper is completed because how can you write the summary of anything which is not yet written? Wealth of terminology is very essential in abstract. Use comprehensive sentences, and do not sacrifice readability for brevity; you can maintain it succinctly by phrasing sentences so that they provide more than a lone rationale. The author can at this moment go straight to shortening the outcome. Sum up the study with the subsequent elements in any summary. Try to limit the initial two items to no more than one line each.

Reason for writing the article—theory, overall issue, purpose.

- Fundamental goal.
- To-the-point depiction of the research.
- Consequences, including definite statistics—if the consequences are quantitative in nature, account for this; results of any numerical analysis should be reported. Significant conclusions or questions that emerge from the research.

Approach:

- Single section and succinct.
- An outline of the job done is always written in past tense.
- Concentrate on shortening results—limit background information to a verdict or two.
- Exact spelling, clarity of sentences and phrases, and appropriate reporting of quantities (proper units, important statistics) are just as significant in an abstract as they are anywhere else.

Introduction:

The introduction should "introduce" the manuscript. The reviewer should be presented with sufficient background information to be capable of comprehending and calculating the purpose of your study without having to refer to other works. The basis for the study should be offered. Give the most important references, but avoid making a comprehensive appraisal of the topic. Describe the problem visibly. If the problem is not acknowledged in a logical, reasonable way, the reviewer will give no attention to your results. Speak in common terms about techniques used to explain the problem, if needed, but do not present any particulars about the protocols here.

The following approach can create a valuable beginning:

- Explain the value (significance) of the study.
- Defend the model—why did you employ this particular system or method? What is its compensation? Remark upon its appropriateness from an abstract point of view as well as pointing out sensible reasons for using it.
- Present a justification. State your particular theory(-ies) or aim(s), and describe the logic that led you to choose them.
- Briefly explain the study's tentative purpose and how it meets the declared objectives.

Approach:

Use past tense except for when referring to recognized facts. After all, the manuscript will be submitted after the entire job is done. Sort out your thoughts; manufacture one key point for every section. If you make the four points listed above, you will need at least four paragraphs. Present surrounding information only when it is necessary to support a situation. The reviewer does not desire to read everything you know about a topic. Shape the theory specifically—do not take a broad view.

As always, give awareness to spelling, simplicity, and correctness of sentences and phrases.

Procedures (methods and materials):

This part is supposed to be the easiest to carve if you have good skills. A soundly written procedures segment allows a capable scientist to replicate your results. Present precise information about your supplies. The suppliers and clarity of reagents can be helpful bits of information. Present methods in sequential order, but linked methodologies can be grouped as a segment. Be concise when relating the protocols. Attempt to give the least amount of information that would permit another capable scientist to replicate your outcome, but be cautious that vital information is integrated. The use of subheadings is suggested and ought to be synchronized with the results section.

When a technique is used that has been well-described in another section, mention the specific item describing the way, but draw the basic principle while stating the situation. The purpose is to show all particular resources and broad procedures so that another person may use some or all of the methods in one more study or referee the scientific value of your work. It is not to be a step-by-step report of the whole thing you did, nor is a methods section a set of orders.

Materials:

Materials may be reported in part of a section or else they may be recognized along with your measures.

Methods:

- Report the method and not the particulars of each process that engaged the same methodology.
- Describe the method entirely.
- To be succinct, present methods under headings dedicated to specific dealings or groups of measures.
- Simplify—detail how procedures were completed, not how they were performed on a particular day.
- If well-known procedures were used, account for the procedure by name, possibly with a reference, and that's all.

Approach:

It is embarrassing to use vigorous voice when documenting methods without using first person, which would focus the reviewer's interest on the researcher rather than the job. As a result, when writing up the methods, most authors use third person passive voice.

Use standard style in this and every other part of the paper—avoid familiar lists, and use full sentences.

What to keep away from:

- Resources and methods are not a set of information.
- Skip all descriptive information and surroundings—save it for the argument.
- Leave out information that is immaterial to a third party.

Results:

The principle of a results segment is to present and demonstrate your conclusion. Create this part as entirely objective details of the outcome, and save all understanding for the discussion.

The page length of this segment is set by the sum and types of data to be reported. Use statistics and tables, if suitable, to present consequences most efficiently.

You must clearly differentiate material which would usually be incorporated in a study editorial from any unprocessed data or additional appendix matter that would not be available. In fact, such matters should not be submitted at all except if requested by the instructor.

Content:

- Sum up your conclusions in text and demonstrate them, if suitable, with figures and tables.
- In the manuscript, explain each of your consequences, and point the reader to remarks that are most appropriate.
- Present a background, such as by describing the question that was addressed by creation of an exacting study.
- Explain results of control experiments and give remarks that are not accessible in a prescribed figure or table, if appropriate.
- Examine your data, then prepare the analyzed (transformed) data in the form of a figure (graph), table, or manuscript.

What to stay away from:

- Do not discuss or infer your outcome, report surrounding information, or try to explain anything.
- Do not include raw data or intermediate calculations in a research manuscript.
- Do not present similar data more than once.
- A manuscript should complement any figures or tables, not duplicate information.
- Never confuse figures with tables—there is a difference.

Approach:

As always, use past tense when you submit your results, and put the whole thing in a reasonable order.

Put figures and tables, appropriately numbered, in order at the end of the report.

If you desire, you may place your figures and tables properly within the text of your results section.

Figures and tables:

If you put figures and tables at the end of some details, make certain that they are visibly distinguished from any attached appendix materials, such as raw facts. Whatever the position, each table must be titled, numbered one after the other, and include a heading. All figures and tables must be divided from the text.

Discussion:

The discussion is expected to be the trickiest segment to write. A lot of papers submitted to the journal are discarded based on problems with the discussion. There is no rule for how long an argument should be.

Position your understanding of the outcome visibly to lead the reviewer through your conclusions, and then finish the paper with a summing up of the implications of the study. The purpose here is to offer an understanding of your results and support all of your conclusions, using facts from your research and generally accepted information, if suitable. The implication of results should be fully described.

Infer your data in the conversation in suitable depth. This means that when you clarify an observable fact, you must explain mechanisms that may account for the observation. If your results vary from your prospect, make clear why that may have happened. If your results agree, then explain the theory that the proof supported. It is never suitable to just state that the data approved the prospect, and let it drop at that. Make a decision as to whether each premise is supported or discarded or if you cannot make a conclusion with assurance. Do not just dismiss a study or part of a study as "uncertain."

Research papers are not acknowledged if the work is imperfect. Draw what conclusions you can based upon the results that you have, and take care of the study as a finished work.

- You may propose future guidelines, such as how an experiment might be personalized to accomplish a new idea.
- Give details of all of your remarks as much as possible, focusing on mechanisms.
- Make a decision as to whether the tentative design sufficiently addressed the theory and whether or not it was correctly restricted. Try to present substitute explanations if they are sensible alternatives.
- One piece of research will not counter an overall question, so maintain the large picture in mind. Where do you go next? The best studies unlock new avenues of study. What questions remain?
- Recommendations for detailed papers will offer supplementary suggestions.

Approach:

When you refer to information, differentiate data generated by your own studies from other available information. Present work done by specific persons (including you) in past tense.

Describe generally acknowledged facts and main beliefs in present tense.

The Administration Rules

Administration Rules to Be Strictly Followed before Submitting Your Research Paper to Global Journals Inc.

Please read the following rules and regulations carefully before submitting your research paper to Global Journals Inc. to avoid rejection.

Segment draft and final research paper: You have to strictly follow the template of a research paper, failing which your paper may get rejected. You are expected to write each part of the paper wholly on your own. The peer reviewers need to identify your own perspective of the concepts in your own terms. Please do not extract straight from any other source, and do not rephrase someone else's analysis. Do not allow anyone else to proofread your manuscript.

Written material: You may discuss this with your guides and key sources. Do not copy anyone else's paper, even if this is only imitation, otherwise it will be rejected on the grounds of plagiarism, which is illegal. Various methods to avoid plagiarism are strictly applied by us to every paper, and, if found guilty, you may be blacklisted, which could affect your career adversely. To guard yourself and others from possible illegal use, please do not permit anyone to use or even read your paper and file.

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Please note that following table is only a Grading of "Paper Compilation" and not on "Performed/Stated Research" whose grading solely depends on Individual Assigned Peer Reviewer and Editorial Board Member. These can be available only on request and after decision of Paper. This report will be the property of Global Journals.

Topics	Grades		
	A-B	**C-D**	**E-F**
Abstract	Clear and concise with appropriate content, Correct format. 200 words or below	Unclear summary and no specific data, Incorrect form Above 200 words	No specific data with ambiguous information Above 250 words
Introduction	Containing all background details with clear goal and appropriate details, flow specification, no grammar and spelling mistake, well organized sentence and paragraph, reference cited	Unclear and confusing data, appropriate format, grammar and spelling errors with unorganized matter	Out of place depth and content, hazy format
Methods and Procedures	Clear and to the point with well arranged paragraph, precision and accuracy of facts and figures, well organized subheads	Difficult to comprehend with embarrassed text, too much explanation but completed	Incorrect and unorganized structure with hazy meaning
Result	Well organized, Clear and specific, Correct units with precision, correct data, well structuring of paragraph, no grammar and spelling mistake	Complete and embarrassed text, difficult to comprehend	Irregular format with wrong facts and figures
Discussion	Well organized, meaningful specification, sound conclusion, logical and concise explanation, highly structured paragraph reference cited	Wordy, unclear conclusion, spurious	Conclusion is not cited, unorganized, difficult to comprehend
References	Complete and correct format, well organized	Beside the point, Incomplete	Wrong format and structuring

INDEX

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