




Impact of Transmission on Resource Adequacy in Systems with Wind and Solar Power

Preprint

E. Ibanez and M. Milligan

To be presented at the 2012 IEEE Power & Energy Society General Meeting
San Diego, California
July 22-26, 2012

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Conference Paper
NREL/CP-5500-53482
February 2012

Contract No. DE-AC36-08GO28308

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information

P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: mailto:reports@adonis.osti.gov

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/help/ordermethods.aspx

Cover Photos: (left to right) PIX 16416, PIX 17423, PIX 16560, PIX 17613, PIX 17436, PIX 17721

Printed on paper containing at least 50% wastepaper, including 10% post consumer waste.

Impact of Transmission on Resource Adequacy in Systems with Wind and Solar Power

Eduardo Ibanez, *Member, IEEE*, and Michael Milligan, *Senior Member, IEEE*

***Abstract*—Variable generation is on track to become a significant contributor to electric power systems worldwide. Thus, it is important to analyze the effect that renewables will have on the reliability of systems. In this paper we present a new tool being implemented at the National Renewable Energy Laboratory, which allows the inclusion of variable generation in the power system resource adequacy. The tool is used to quantify a first estimate of the potential contribution of transmission to reliability in highly interconnected systems and an example is provided using the Western Interconnection footprint.**

***Index Terms*—Power transmission, power systems reliability, probability, solar energy, wind energy.**

I. Introduction

THE increasing amount of electrical load served by variable generation (VG), such as wind and solar energy, in the United States and many other countries has stimulated an interesting line of research to better quantify the capacity value of these resources. Methods applied traditionally to thermal units based on their average outage rates do not apply to VG because of their uncertain and non-dispatchable nature. The North American Electric Reliability Corporation's (NERC's) Integration of Variable Generation Task Force (IVGTF) recently released a report that highlighted the need to develop and benchmark metrics that reasonably and fairly calculate the capacity value of solar and wind power [1]. As the fraction of generation coming from VG becomes more relevant, their estimated capacity value will have an impact on system planning [2].

In this paper, we provide a method to include VG in traditional probabilistic-based adequacy methods. This method has been implemented in the Renewable Energy Probabilistic Resource Assessment tool (REPRA). Through an example based on the U.S. Western Interconnection (WI), this method will be applied to assess a first order approach of the effect that transmission can have in system adequacy. The results are significant enough to encourage further investigation, which would provide a better estimate of the contribution of transmission and allow a comprehensive analysis of the trade-offs between the addition of new transmission and new generation.

The remainder of the paper is organized as follows: Section II introduces the concept of effective load carrying capability; Section III describes the REPRA tool used in this study; Section IV provides a numerical example that applies this methodology to the Western Interconnection; and, finally, Section V concludes and provides future steps.

E. Ibanez and M. Milligan are with the National Renewable Energy Laboratory (NREL), 1617 Cole Blvd., Golden, CO 80401 USA (e-mail: eduardo.ibanez@nrel.gov, michael.milligan@nrel.gov).

II. Effective Load Carrying Capability

Generation system adequacy is the portion of electrical systems reliability that ensures that available capacity is sufficient to meet expected system demand within an acceptable risk threshold [3] at some future date. The metrics most commonly used to assess system adequacy revolve around probabilistic methods based the loss of load probability (LOLP). The loss of load expectation (LOLE) is a measurement of the expected days in a year that could face a generation shortfall. Similarly, the loss of load hours (LOLH) measures the expected number of hours in a year with insufficient generation.

The literature review in [4] and more recent examples in [1], [5] present the effective load carrying capability (ELCC) as an emerging suitable metric to evaluate the effect of VG. Given a reliability target, ELCC is defined for a system as the maximum load that could be served by the system while meeting said reliability target. We also can define the ELCC for a generation unit as the increase in the system ELCC when that unit is added to the system. Fig. 1 shows a graphical representation of this definition. The red horizontal line represents the reliability target of 1 day in 10 years, which is a common target used in industry. The blue line represents the reliability curve for the units already in the system, which has an ELCC of 10 GW. When a new generation unit is added the reliability curve shifts to the right. The horizontal difference between the systems curves, 400 MW, represents the new unit's ELCC.

These calculations can be used to estimate the beneficial contribution to system adequacy from a transmission layout. Consider the different areas that are connected by said transmission layout. We could calculate the system ELCC for the resources in each area, essentially isolating them from each other. Since it is highly unlikely that the balance of resources and load is evenly distributed along the entire footprint, the transmission system can facilitate the transfer of extra generation capacity to the most problematic areas. Thus, the combination of the individual areas' ELCC will be smaller than that of the entire footprint. The different between these

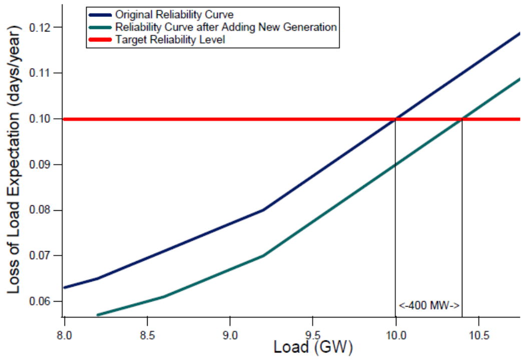

Fig. 1. The unit ELCC is the horizontal distance between the reliability curves, measured at the target reliability level (400 MW at 1d/10y).

metrics is the estimated adequacy contribution from the transmission system. The upper bound of this contribution can be found by comparing the individual areas to a copper sheet model, where perfect transmission is assumed between any two points in the system.

This methodology was used in NREL's Eastern Wind Integration Study (EWITS) [6], which found that the existing grid transmission system in the Eastern Interconnection provides between 1,200 and 8,500 MW of tie benefits, depending on the load profiles used.

This simple representation of region connectivity allows us to evaluate the potential of performing a more detailed analysis with proper transmission representation. In reality, transmission capacity is a finite and probabilistic value. Transmission lines, like conventional generators, should be represented with a forced outage rate and a maximum capacity. We envision incorporating these capabilities into the REPRA tool, although analytical examples available in the literature are limited to two or three interconnected areas [3], [7]. Alternative methodologies include the use of Monte Carlo simulations, e.g., in GE's Multi-Area Reliability Simulations (MARS) program [8].

III. The REPRA Tool

The Renewable Energy Probabilistic Resource Adequacy tool (REPRA) is being developed at NREL to better understand how different types of renewable generation, which are usually non-dispatchable sources of power, can contribute to a power systems adequacy, from a reliability point of view.

At the core of the model resides a fast convolution algorithm that combines the probability distribution of the traditional generators. These are represented by a finite number of states. The most simple case is whether the unit is available or not, with a probability that it is not equal to the Effective Forced Outage Rate (EFOR).

Once the convolution of the traditional units [3] has been performed, the result is a capacity outage probability table, which indicates the LOLP for all levels of load the system can serve. For instance, Table I shows the result when considering six 50 MW units with an EFOR of 8%. The third row shows that the probability of an outage of 100 MW is 0.0688, which is equivalent to the probability of any two units being out of service. Similarly, the cumulative probability of an outage exceeding 100 MW is 0.0773; alternatively, one can interpret this cumulative probability as the LOLP associated with a 200 MW load level.

TABLE I
Capacity Outage Probability Table for Conventional Units

MW-OUT	MW-IN	Probability	LOLP
0	300	0.6064	1.0000
50	250	0.3164	0.3936
100	200	0.0688	0.0773
150	150	0.0080	0.0085
200	100	5.20E-04	5.38E-04
250	50	1.81E-05	1.84E-05
300	0	2.62E-07	2.62E-07

Variable generation can be convolved with the capacity outage probability table in a similar fashion. The main difference is the determination of the probability distribution used in the convolution. Unlike traditional generators, VG production is limited by available resources such as wind speed or solar irradiance, which are governed by weather patterns. To preserve this variation, we make use of a sliding window technique [9] for all hours of the year. Figure 2 shows a graphical representation of a sliding window, which includes the current and adjacent hours. The width is predetermined and, in this case, it includes a total of five hours. Power outputs in the window are then given equal probability and sorted, providing the necessary probability distribution that will be included in an equivalent outage table (Table II). This table would then be convolved with the results in Table I to obtain the total system outage table (Table III). This table was truncated for LOLP values below 0.001.

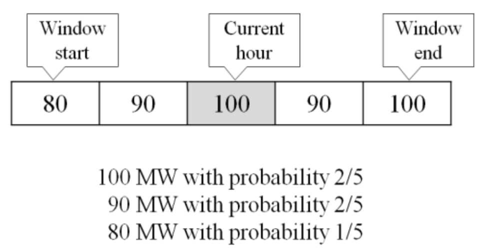

Fig. 2. Example of sliding window for wind power generation.

TABLE II
Capacity Outage Probability Table for Wind Sliding Window

MW-OUT	MW-IN	Probability	LOLP
0	100	0.4	1.0
10	90	0.4	0.6
20	80	0.2	0.2

REPRA allows the study of resource adequacy for different levels of geographic aggregation. This will contribute to a better understanding of the contribution of VG and also, as in this case, to better determine the benefits of a more interconnected system.

TABLE III
EXAMPLE OF CAPACITY OUTAGE PROBABILITY TABLE

MW-OUT	MW-IN	Probability	LOLP
0	400	0.243	1.000
10	390	0.243	0.757
20	380	0.121	0.515
50	350	0.127	0.394
60	340	0.127	0.267
70	330	0.0633	0.141
100	300	0.0275	0.077
110	290	0.0275	0.050
120	280	0.0138	0.022
150	250	0.0032	0.008
160	240	0.0032	0.005
170	230	0.0016	0.002

IV. NUMERICAL EXAMPLE

A. Data description

In this section, we apply the reliability tool introduced in the previous section to the Western Electricity Coordinating Council (WECC) footprint. The representation of the generation fleet is based on the upcoming Phase 2 of NREL's Western Wind and Solar Study (WWSIS) [10]. This data is consistent with other studies performed by the WECC's Transmission Expansion Planning Policy Committee (TEPPC) [11].

Table IV contains the list of Balancing Area Authorities (BAAs) that were considered in this example. BAAs were grouped in seven subregions, following the suggested zones in [12], with the only difference being that the Southern California subregion includes the Comisón Federal de Electricidad (CFE). Figure 3 presents a map of the different BAAs and the subregions they belong too, which are differentiated by different shades. In this example WAUW is merged into NWMT due to the small size of the former.

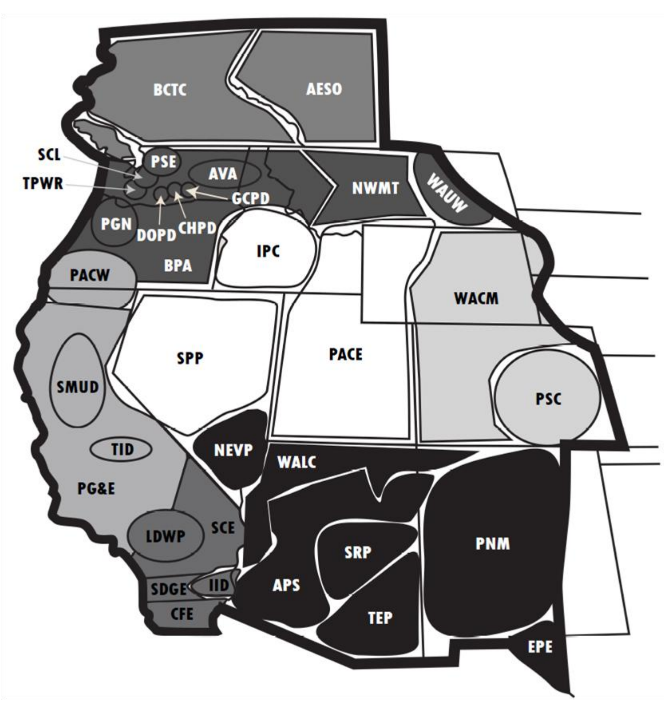

Fig. 3. WECC Balancing Authority Areas and subregions.

Load time series data from 2006 was chosen from the Ventyx Velocity Suite [13] and was increased to represent the load in 2020, the focus year. The wind dataset was derived from the large wind speed and power database [14] developed by 3TIER using a numerical weather prediction (NVP) model applied to the West. Because the model allows for the recreation of the weather, at any time and space, wind speed data was sampled at representative hub heights for modern wind turbines every 10 minutes for a 3 year period on a 2-km spatial resolution. The resulting dataset was then used to construct the 2006 time series, which was paired with the 2006 load data time series to preserve the consistency of common weather impacts. Solar data was produced by NREL [15] based on the satellite-derived irradiance generated by the State University of New York/Clean Power Research [16], which is available on a 10-km grid at an hourly resolution. The resulting dataset contains a total of 29 GW of installed wind and 14 GW of solar, which correspond to energy penetrations of 8% and 3% for wind and solar power, respectively.

TABLE IV
BALANCING AUTHORITIES AND SUBREGIONS IN WECC

Subregion	Code	Balancing Authority Area
Canada	AESO	Alberta
	BCTC	British Columbia Transmission Corporation
Northwest	AVA	Avista
	BPA	Bonneville Power Administration
	CHPD	PUD No 1 of Chelan County
	DODP	PUD No 1 of Douglas County
	GCPD	PUD No 1 of Grant County
	NWMT	Northwest Energy
	PGN	Portland General Electric
	PSE	Puget Sound Energy
	SCL	Seattle City Light
	TPWR	Tacoma Power
	WAUW	WAPA - Upper Great Plains West
Basin	IPC	Idaho Power Corp.
	PACE	Pacificorp East
	SPP	Sierra Pacific Power (NV Energy)
Rockies	PSC	Public Service Company of Colorado
	WACM	WAPA - Colorado Missouri Region
Desert Southwest	APS	Arizona Public Service
	EPE	El Paso Electric
	NEVP	Nevada Power
	PNM	Public Service Company of New Mexico
	SRP	Salt River Project
	TEP	Tucson Electric Power
	WALC	WAPA - Lower Colorado Region
Northern California	PACW	Pacificorp West
	PG&E	Pacific Gas and Electric
	SMUD	Sacramento Municipal Utility District
	TID	Turlock Irrigation District
Southern California	IID	Imperial Irrigation District
	LDWP	LA Dpt. of Water and Power
	SCE	Southern California Edison
	SDGE	San Diego Gas and Electric
	CFE	Comisón Federal de Electricidad

B. Results

The methods described in the previous sections were applied to the Western Interconnection footprint. Table V summarizes the main characteristics of the interconnection and its different subregions. The data includes the coincident load peak by region, along with the number of thermal and hydro units (conventional) and the capacity they represent, along with installed wind and solar capacity. The last column includes the resulting LOLE when the regions are analyzed by themselves, which is smaller than the usual 1 day in 10 years for the entire interconnection and most subregions. The Basin region and Southern California routinely import energy from other areas, which is consistent with the resulting high LOLE values.

TABLE V
REGIONS CHARACTERISTICS AND BASIC LOLE RESULTS

Region	Peak (GW)	Units	Conventional capacity (GW)	Wind (GW)	Solar (GW)	LOLE (days/y)
Interconnect	177.6	1901	251.2	29.1	14.3	$< 10^{-10}$
Canada	26.3	298	62.8	4.1	–	$< 10^{-10}$
Northwest	32.2	454	46.5	9.7	1.5	$< 10^{-10}$
Basin	16.4	167	17.0	2.5	–	4.53
Rockies	13.9	164	16.0	3.3	1.1	0.015
Desert SW	33.1	239	40.9	1.3	1.1	$< 10^{-10}$
North CA	28.5	284	31.2	2.4	1.8	0.014
South CA	41.6	295	36.7	5.9	8.8	2.95

ELCC values are calculated with and without a contribution from VG at three levels: interconnection, subregions, and BAAs. In each case, transmission constraints between units in the same area are dismissed. The results for the first two levels are summarized in Table VI, including the maximum peak loads that could be served by the installed generation within each area with an LOLE of 1 day in 10 years. The scale factors correspond to the ratio between this maximum peak and the actual peak load in Table V. Similar results are found at the BAA level but are omitted here.

TABLE VI
SYSTEM ELCC RESULTS FOR INTERCONNECTION AND SUBREGIONS

Region	VG included		VG excluded	
	Scale factor	Peak load (GW)	Scale factor	Peak load (GW)
Interconnect	1.373	244.0	1.304	231.6
Canada	2.014	52.9	1.952	51.3
Northwest	1.354	43.6	1.308	42.2
Basin	0.900	14.8	0.883	14.5
Rockies	1.041	14.4	0.979	13.6
Desert SW	1.152	38.1	1.090	36.1
North CA	1.028	29.3	0.985	28.1
South CA	0.884	36.8	0.802	33.3

The smaller regions VI need to be properly combined to be able to compare interconnection-wide results for all three aggregation levels. For instance, the load time series for each subregion is scaled using the appropriate factor. The sum of these load series is then used to find the new coincident interconnection-wide peak that can be served without violating the minimum LOLE for each subregion. The same process is performed starting with the BAA data and summarized in Table VII. The increase column shows the additional peak load that can be served when higher levels of aggregation are compared to the isolated BAA case. According to these results, perfect transmission between BAAs in the WI would allow the system to supply an additional 60.3 GW of peak load when VG is factored in. Half of that extra load could be served if we only considered perfect transmission within each subregion.

TABLE VII
COINCIDENT PEAK LOAD AND AVERAGE POWER BY AGGREGATION LEVEL

Region	VG	Peak load (GW)	Increase (GW)
Intercon.		244.0	60.3 (33%)
Subregion	Yes	209.4	25.7 (14%)
BAAs		183.7	
Intercon.		231.6	56.3 (32%)
Subregion	No	199.3	24.0 (14%)
BAAs		175.3	

The relative increase in peak load that could be served is very similar whether or not VG has been factored in: 33% for perfect interconnection transmission and 14% for infinite intra-subregional transmission. Additionally, we can examine the contribution of VG to the system adequacy by calculating the differences between the same aggregation levels with and without renewables. The results are displayed in Table VIII and correspond to the ELCC for the combined wind and solar power present in the system, and their average capacity value. Since these values increase with the level of aggregation, we can conclude that transmission also has a boosting effect on the contribution of VG to system adequacy.

TABLE VIII
ELCC AND CAPACITY FACTOR FOR RENEWABLES BY AGGREGATION LEVEL

Region	VG ELCC (GW)	VG Capacity Value (%)
Intercon.	12.4	28.2
Subregion	10.1	23.0
BAAs	8.4	19.1

V. CONCLUSIONS

The methodology presented here is promising in quantifying the beneficial contribution of transmission to electric system adequacy. To gain a better understanding of this contribution this approach needs to be applied to other cases, including alternative footprints, historical time series data, and penetration levels of renewable generation.

The numerical example in this paper analyzes the contribution that perfect transmission has in the adequacy of a system. The results indicate that this contribution is significant. Furthermore, additional transmission enhances the capacity value of variable generation.

The promising results suggest that further work should be done to extend the methodology so that it is possible to enforce actual transmission constraints and force outage rates, as opposed to the copper-sheet analysis used in this paper. The result of this work will produce a more accurate estimation of the value of transmission in terms of resource adequacy.

VI. REFERENCES

[1] Integration of Variable Generation Task Force. (2011) "Methods to Model and Calculate Capacity Contributions of Variable Generation for Resource Adequacy Planning," North American Electric Reliability

Corporation, Princeton, NJ. [Online]. Available: http://www.nerc.com/docs/pc/ivgtf/IVGTF1-2.pdf).

[2] M. Milligan, and K. Porter "Wind Capacity Credit in the United States," in *Proc. 2008 IEEE Power and Energy Society Gral. Meeting*, pp. 1-5.

[3] R. Billinton, and R. N. Allan, *Reliability evaluation of power systems*, New York: Plenum Press 1996.

[4] M. Milligan, and K. Porter, "Determining the Capacity Value of Wind: An Updated Survey of Methods and Implementation," in *Proc. of WindPower 2008*.

[5] A. Keane, Keane, M. Milligan, C.J. Dent, B. Hasche, C. D'Annunzio, K. Dragoon, H. Holttinen, N. Samaan, L. Soder, M.A. O'Malley, "Capacity Value of Wind Power," *IEEE Trans. on Power Syst.*, vol. 26, no. 2, pp.564-572, May 2011.

[6] Enernex. (2010) "Eastern Wind and Transmission Study," National Renewable Energy Laboratory, Golden, CO, Tech. Rep. SR-5500-47078. [Online]. Available: http://www.nrel.gov/wind/systemsintegration/ewits.html

[7] L. Goel, C.K. Wong, and G.S. Wee, "And Educational Software Package for Reliability Evaluation of Interconnected Systems," *IEEE Trans. Power Systems*, Vol. 10, No. 3, pp. 1147-1153, Aug. 1995.

[8] G.E. Haringa, G.A. Jordan, L.L. Garver, "Application of Monte Carlo Simulation to Multi-Area Reliability Evaluation," *IEEE Computer Applications in Power*, Vol. 4, pp. 21-25, Jan. 1991.

[9] M. Milligan. (200), "A Chronological Reliability Model Incorporating Wind Forecasts to Assess Wind Plant Reserve Allocation," National Renewable Energy Laboratory, Golden, CO. [Online]. Available: http://www.nrel.gov/docs/fy02osti/32210.pdf

[10] GE Energy. (2010) "Western Wind and Solar Integration Study," National Renewable Energy Laboratory, Golden, CO, Tech. Rep. SR-550-47434. [Online]. Available: http://www.nrel.gov/wind/systemsintegration/wwsis.html

[11] Western Electricity Coordinating Council. (2009) "Transmission Expansion Planning Policy Committee 2009 Study Program Results Report." [Online]. Available: www.wecc.biz/committees/BOD/TEPPC/Shared Documents/TEPPC Annual Reports/

[12] Western Electricity Coordinating Council. (2010) "2010 Power Supply Assessment." [Online]. Available: http://www.wecc.biz/Planning/ResourceAdequacy/PSA/)

[13] Ventyx. (2010) "Energy Market Data." [Online]. Available: http://www.ventyx.com/velocity/energy-market-data.asp

[14] 3TIER. (2010) "Development of Regional Wind Resource and Wind Plant Output Datasets", National Renewable Energy Laboratory, Golden, CO, Tech. Rep. NREL/SR-550-47676. [Online]. Available: http://www.nrel.gov/docs/fy10osti/47676.pdf

[15] K. Orwigm M. Hummon, B.-M. Hodge, and D. Lew, "Solar Data Inputs for Integration and Transmission Planning Studies," *Proc. 1st Int. Workshop on Integration of Solar Power into Power Systems*, Aarhu, Denmark, Oct. 2011.

[16] S. Wilcox, M. Anderberg, R. George, W. Marion, D. Myers, D. Renne, N. Lott, T. Whitehurst, W. Beckman, C. Gueymard, R. Perez, P. Stackhouse, and F. Vignola, "Completing Production of the Updated National Solar Radiation Database for the United States," NREL Report No. CP-581-41511, July 2007.

VII. Biographies

Eduardo Ibanez (StM'08, M'11) received in the Diploma degree in Industrial Engineering from Universidad Pública de Navarra, Pamplona, Spain. He graduated from Iowa State University, Ames, IA with a Ph.D. degree in Electrical Engineering and a M.Sc. degree in Statistics.

In May 2011, he joined the grid integration team at the National Renewable Energy Laboratory, Golden, CO, USA. His research interests include studying high levels of renewable energy penetration, transmission planning, and the integration of energy and transportation systems.

Michael Milligan (M'98, SM'10) received a B.A. degree from Albion College, Albion, MI, and the M.A. and Ph.D. degrees from the University of Colorado, Boulder.

He is Principal Researcher in the Transmission and Grid Integration Group at the National Renewable Energy Laboratory, Golden, CO, USA. He has worked on most aspects of wind/solar integration since coming to NREL in 1992, and has published more than 140 technical reports, papers, and book chapters. He participates in the NERC Variable Generation Task Force, WECC's Variable Generation Subcommittee, and the International Energy Agency Task 25. He has served on numerous technical review committees for wind integration studies, provided testimony at public utility commission hearings and workshop presentations, and served on the Wind Task Force for the Western Governors' Association Clean and Diverse Energy project.