National Wind Energy Workforce Assessment Methods Report: Surveys and System Dynamics Model

Brinn McDowell and Jeremy Stefek

National Renewable Energy Laboratory

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List of Acronyms

BAU	business as usual
CLD	causal loop diagram
DOE	U.S. Department of Energy
FTE	full-time equivalent
IRA	Inflation Reduction Act
JEDI	Jobs and Economic Development Impact
MW	megawatt
NREL	National Renewable Energy Laboratory

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1 Purpose

This report documents the methodology for the *National Wind Workforce Assessment: Challenges, Opportunities, and Future Needs* (McDowell et al. 2024) report. Here, the authors will describe how multiple survey efforts and system dynamics modeling have been used to estimate wind energy workforce needs and conduct a sensitivity analysis. We conducted workforce estimation and sensitivity analysis to help inform actions that can be used to ensure that workforce planning in the industry is done in a way that is sustainable.

Workforce planning is defined as "the practice of determining the demand that will be placed on the workforce of an enterprise at some time in the future, in terms of required effort, and hence the number, skills, and proportion of people required. Following this, determining how those demands will be met through developing workforce or human resources (HR) plans" (Cave and Willis 2020). System dynamics is a computer-based model that "quantifies interactions and develops a time-dependent view of how a complex system behaves to help design more effective policy changes" (System Dynamics Society 2022). This methods report is intended for people who are interested in informing their workforce planning approaches through system dynamics modeling and supportive survey information.

This methods report is organized into the following three main sections that correlate with the research methods used for the *National Wind Workforce Assessment: Challenges, Opportunities, and Future Needs* (McDowell et al. 2024) report:

1. Discusses the methodology behind the four key stakeholders' surveys
2. Details the creation of the system dynamics workforce model
3. Explains how the survey results were normalized to create a baseline workforce estimation within the system dynamics model and explains how the scenarios were simulated.

2 Survey Effort

Over the past decade, the National Renewable Energy Laboratory (NREL) has conducted periodic survey efforts to inform various national-level wind workforce assessments. The first survey was conducted in 2012, with the intention to better understand the status of the domestic wind workforce, estimate the future workforce needs, and determine whether existing and new training and educational programs can meet the future wind industry workforce demands (Leventhal and Tegen 2013). These objectives continued to be explored through follow-on survey efforts in 2017, 2020, and most recently in 2022, which correspond to reports published in 2019, 2022, and 2023, respectively. In 2022, NREL and BW Research distributed surveys to the following four key workforce groups:

1. Wind industry employers
2. Education and training programs
3. Current and recent[1] students
4. Current and recent[2] wind employees.

Ultimately, the data collected in the 2022 survey effort helped inform key levers, data inputs, and behaviors modeled within the system dynamics model that we used to estimate the national wind workforce from 2021 through 2050 for both offshore and land-based wind energy. We define key levers as actions that influence workforce supply and demand such as automation, perception of wind energy industry jobs, and acceptance rates. Lists of the key levers are included in Table 2 and Table 3.

2.1 Background

In *A National Skills Assessment of the U.S. Wind Industry in 2012* (Leventhal and Tegen 2013), the survey data revealed that wind industry firms were facing hiring challenges, and introduced the idea that more education and training institutions were needed to meet the estimated future wind employment demand. The second report, *The Wind Energy Workforce in the United States: Training, Hiring, and Future Needs* (Keyser and Tegen 2019), further expanded the 2012 survey effort to include not only wind industry employers, but also education and training programs. The addition of education and training programs in the 2017 survey effort helped further explore if education and training institutions had the ability to meet the future estimated wind workforce demand. Additionally, the 2019 report, which was informed by the 2017 survey effort, concluded that there was a gap between students who graduate and are hoping to work in the wind industry and firms that are hiring for the wind industry but cannot connect with qualified students. However, the reasons for the workforce gap were uncertain at the time.

In 2020, a third survey was conducted to help identify the reasons for the U.S. wind industry workforce gap (Stefek et al. 2022). This survey effort targeted wind industry employers and current and recent students to interpolate the root causes of the workforce gap from both perspectives. Through this research, the wind workforce gap was defined as a disconnect between wind industry employers, the workforce, and educational institutions—wind energy

[1] For this survey, we define recent students as student who graduated within the last 3 years.
[2] For this survey, we define recent employees as having worked in the wind industry in the last 3 years.

employers reported having difficulty finding qualified candidates while the potential wind energy workforce (e.g., students and recent graduates) reported difficulty finding jobs, and educational institutions reported having difficulty placing students in jobs (Stefek et al. 2022). Additionally, a lack of education and training, inadequate experience, and too few applicants were noted as the top three hiring barriers according to wind energy firms. Alternatively, getting relevant experience, finding employment in a desirable geographic location, and developing technical skills were indicated by the total workforce as their top three challenges to being hired. *The National Wind Workforce Assessment: Challenges, Opportunities, and Future Needs* (McDowell et al. 2024) report expands on these previous efforts by providing 2022 survey data to inform the status of the wind workforce gap and identify actionable steps that can be taken to mitigate its effects.

All four survey efforts follow the same general methods for research; however, each survey collected additional information based on the findings from the previous reports. Table 1 displays the stakeholders targeted in the associated survey effort and the number of completions each effort had per stakeholder group. The 2022 survey effort was the first time that wind industry employers; education and training programs; current and recent students; and current and recent wind employees were surveyed together. Furthermore, it was the first time that data from the current and recent wind employees were collected. Appendix A.1 displays the surveys that were conducted in the 2022 survey effort.

Table 1. Survey Completion Number and Type of Stakeholders in 2012, 2017, 2020, and 2022[3]

	2012 Data	2017 Data	2020 Data	2022 Data
Wind Industry Employers	418 completions 10% response rate 85% completion rate	247 completions 10% response rate 92% completion rate	296 completions 14% response rate 87% completion rate	228 completions 7% response rate 81% completion rate
Education and Training Programs		68 completions 61% completion rate		27 completions 14% response rate 92% completion rate
Current and Recent Students			At participating institutions: 563 completions With relevant degrees: 206 completions 17% response rate 90% completion rate	304 completions 38% response rate 98% completion rate
Current and Recent Wind Employees				29 completions Linked from student survey, no sample 73% completion rate

2.2 Survey Limitations

When creating the 2022 national wind workforce assessment surveys, we mitigated bias in the responses by avoiding leading and double- barreled[4] questions and not using jargon. However, despite these efforts, the team at NREL recognizes that the data represented in the *National Wind Workforce Assessment: Challenges, Opportunities, and Future Needs* (McDowell et al. 2024) may be more representative of specific stakeholder groups based on respondent participation. To delve into this further, background information on previously run surveys, methods used for contacting survey participants, and survey participant demographics are discussed in the following sections.

2.3 Methods

While similar methods were conducted in previously run survey efforts, this report focuses on the methods used for the 2022 survey effort. NREL contracted with BW Research Partnership to survey current students, recent graduates, educators, and wind energy employers in the United States, resulting in a total of 630 completions across all surveys.

Some of the objectives of the 2022 survey effort included (BW Research 2023):

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[3] The response rate is defined as the share of people who responded to the survey instrument in comparison to the amount of people the survey instrument was sent to, and the completion rate is the share of the people who completed the survey out of the people who responded to the survey.

[4] A double-barreled question is a question that asks about two different topics while only allowing for a single answer.

- Better understanding and quantifying the employment priorities of wind energy employers. This included the adoption of automation technologies, the occupational makeup of wind energy firms, recruitment strategies and pipelines, and hiring challenges and needs.
- Profiling current and potential wind energy industry workers about educational and training attainment, career satisfaction, employment and job searching challenges, and wind energy program participation.
- Quantifying interest in and awareness of wind energy jobs and opportunities among potential workers, including perceptions of wind industry employment attributes, benefits, and challenges to wind industry employment and occupational preferences.

2.3.1 Employer Survey

The employer survey was available from August 9, 2022, to October 6, 2022, resulting in a total of 3,224 emails (with up to six reminders), and 2,500 phone calls (with up to three reminders) conducted. In total, 228 wind energy industry employers completed the survey from across the United States. According to BW Research, the audience for the employer survey included (BW Research 2023):

- A recontact sample from the *United States Energy and Employment Report* (DOE 2022a) of wind energy employers
- A recontact sample from the prior NREL wind energy workforce survey from 2020
- A sample of American Clean Power members
- An online panel of employers that met all screener qualifications for wind energy.

Large firms (50+ employees) with land-based wind energy involvement had the most representation within the employer survey. Of the wind energy employers who responded to the survey, 93% reported being involved with land-based wind in some way. Furthermore, 50.4% reported having some involvement with offshore wind, and 7.0% reported only being involved in offshore wind. When asked about firm size, 61.8% reported to have at least 50 employees (large firm), 18.4% reported having between 10 and 49 employees (midsized firm), and 19.7% reported to have between 1 and 9 employees (small firm).

There was relatively even distribution of representation from firms that represent different industry segments (Figure 1). Operation and asset management, development and siting, and construction were the top three wind industry segments, as indicated by employer respondents.

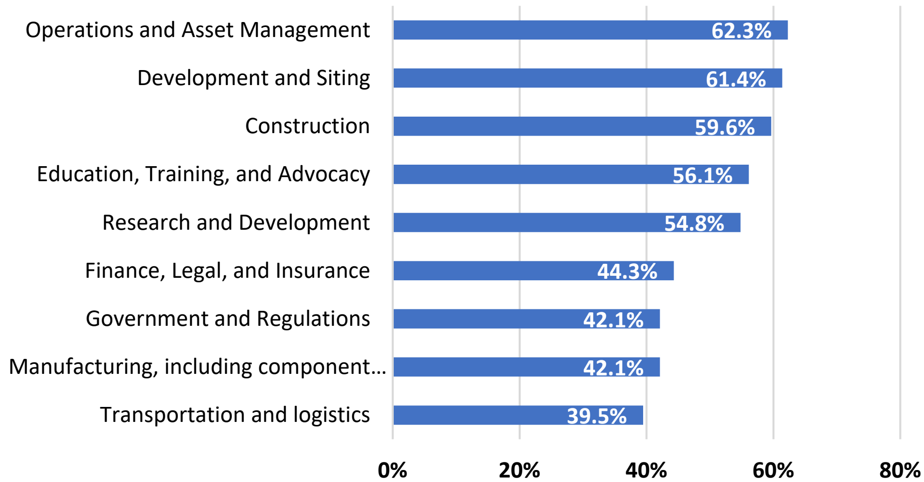


Figure 1. Involvement in wind industry segments, 2022 (n=228). ***Graph from BW Research Partnership (2023)***

2.3.2 Student Baseline and Tracker Survey

Within the student baseline (new student cohort) and tracker survey (students who had completed a survey in a prior year), students were defined as individuals who are currently completing or have completed their degree or certification within the last 3 years that are in a wind-energy-specific program or a field of study that is relevant to wind industry jobs including engineering, finance, and vocational trades.

The student baseline survey was available from September 9, 2022, to October 13, 2022, resulting in 286 completions who could consider employment in the industry. The survey was emailed to 148 Collegiate Wind Competition participants (with up to six reminders), and additional links were shared with relevant institutions. These links were then forwarded to students and/or recent alumni.

The student tracker survey was conducted from August 31, 2022, to October 5, 2022, resulting in 60 completions from previous respondents. Previous contacted students were emailed (156 sent with up to six reminders) and called (up to two reminders).

For both the baseline and tracker survey university students had the largest representation comprising 69.5% of all current and recent student respondents. Further, community college students comprised 27.9% of student respondents and trade schools comprised the remaining 2.6%.

As shown in Figure 2, when assessing the degree student and recent graduates are/were working toward, finance, accounting, and/or business were the most represented.

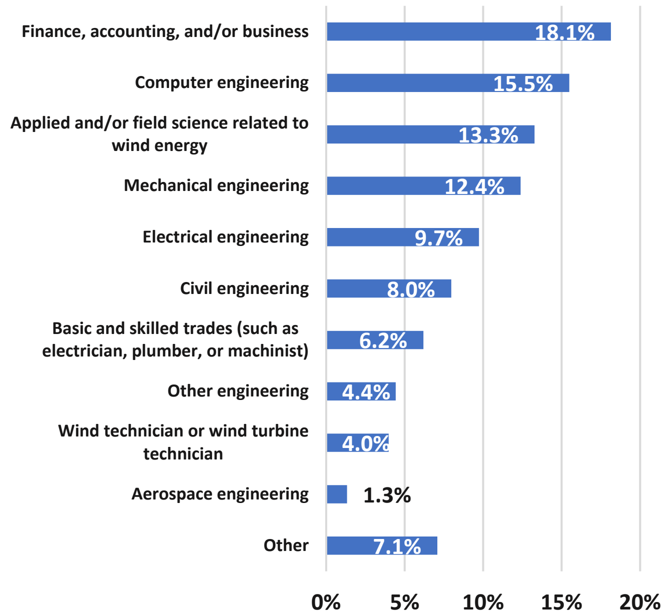


Figure 2. Degrees students and recent graduates were/are working toward, 2022 (n=226). ***Graph from BW Research Partnership (2023)***

2.3.3 Current and Recent Wind Employee Survey

The current and recent employee survey was open from September 10–October 11. The respondents of this survey were recruited from the student survey based on a response that they are currently working in the wind industry. This survey had a total of 29 completions. This was the first year that current and recent wind employees were surveyed. As shown in Figure 3, current and recent wind employee respondents had the most involvement in the land-based wind energy sector. Furthermore, the respondents were primarily entry-level (48.3%) to midlevel (37.9%) employees with less representation from people who hold senior-level positions (10.3%).

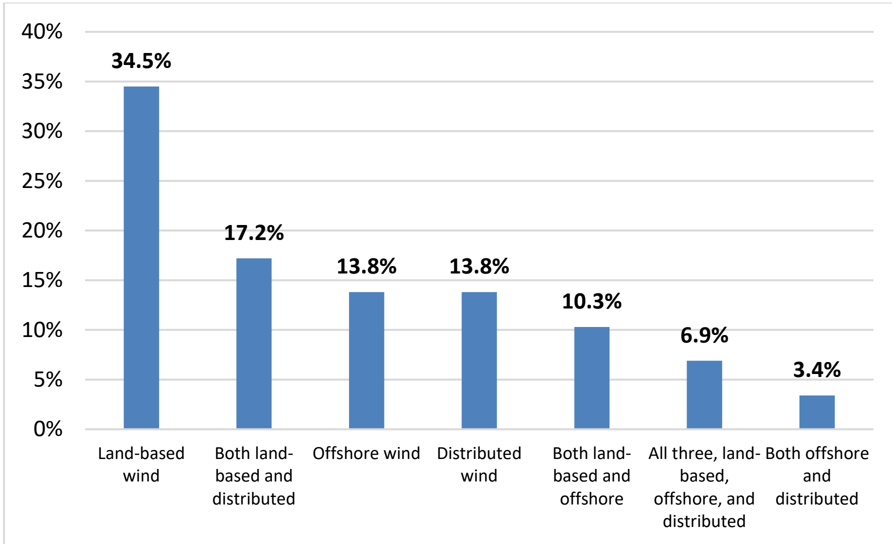


Figure 3. Primary sector of work in the wind industry (n = 29)

Additionally, 48.3% of employee respondents were wind technicians, followed by finance accounting and business, and basic skills (13.8%) (Figure 4).

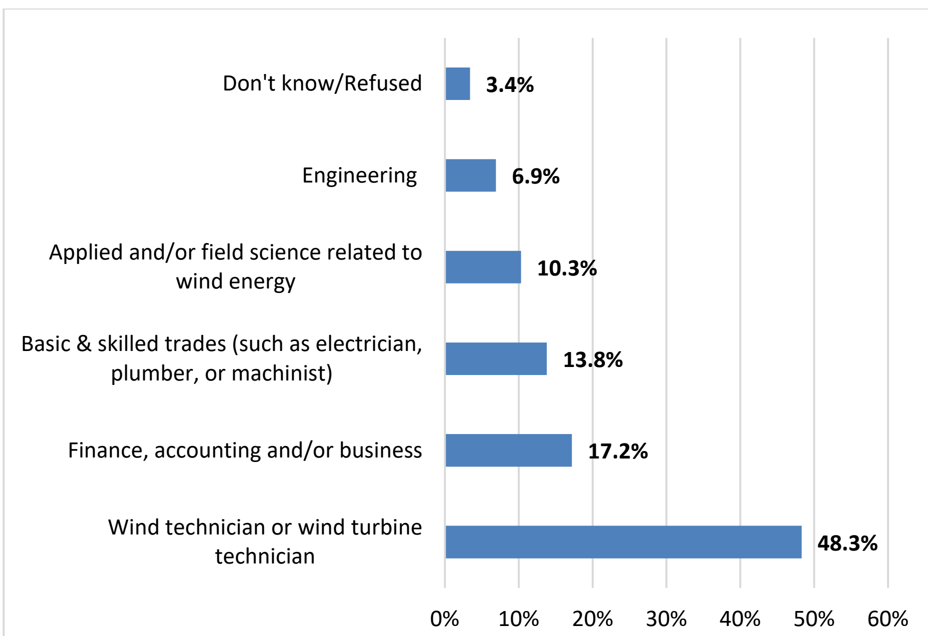


Figure 4. Area of study held (n = 29)

2.3.4 Educator Survey

Educators came from various sources, such as the Collegiate Wind Competition and the North American Wind Energy Academy and agreed to be contacted via email. A total of 27 educators responded to the survey and mostly represent programs that have a connection to NREL, or programs sponsored by DOE's Wind Energy Technologies Office. The last educators survey was conducted in 2017. Educators from both universities and community colleges were represented (Figure 5). Figure 6 displays the type of programs that the educators taught.

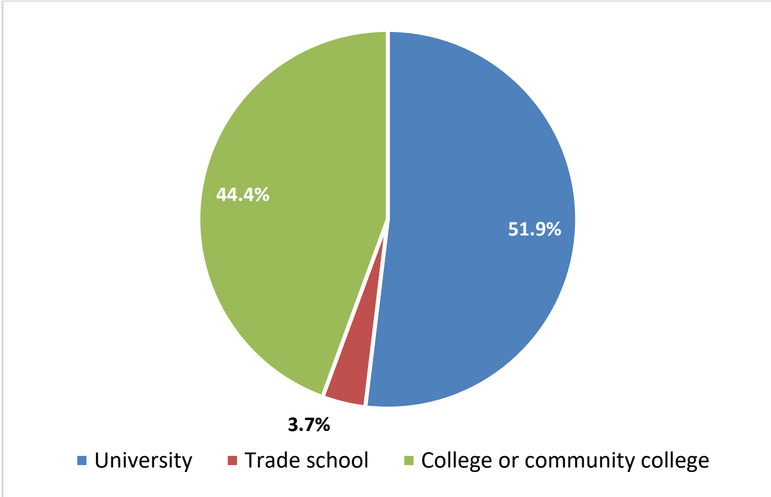


Figure 5. Type of school currently employed (n=27)

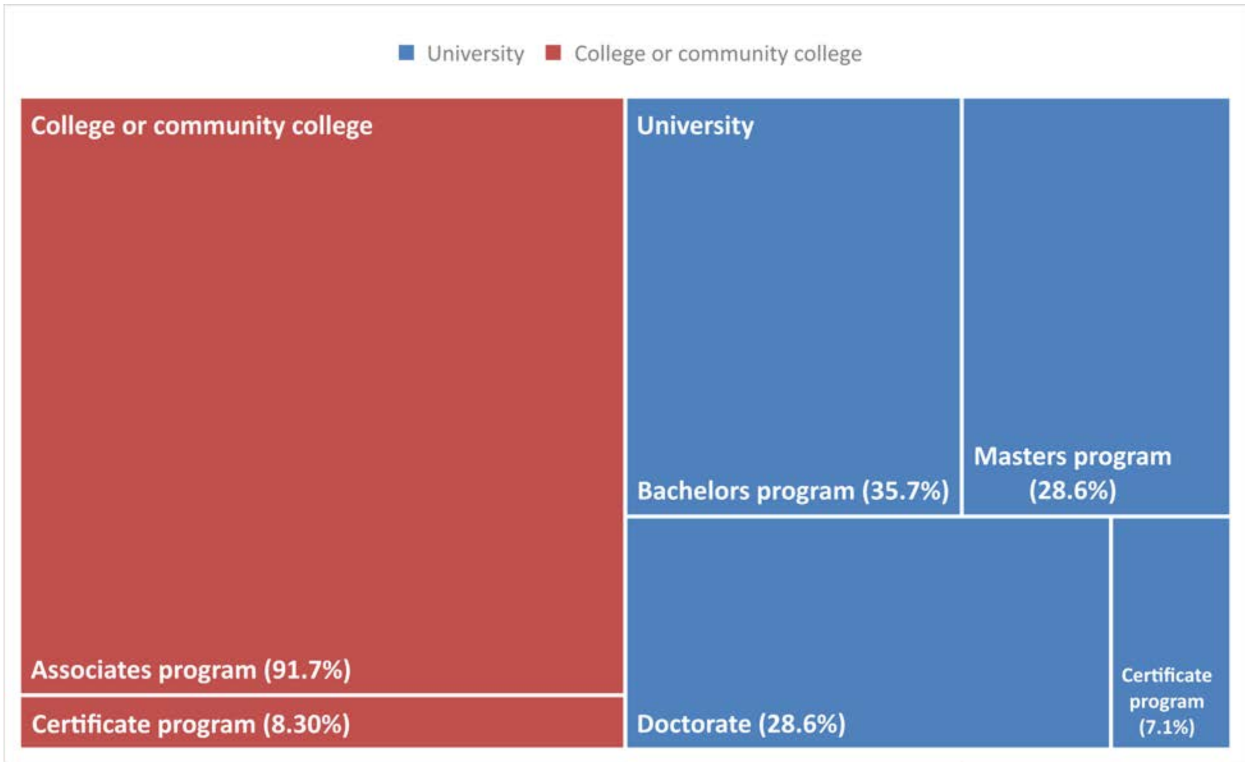


Figure 6. Type of school program (n=14, n =12)

Furthermore, the educator survey participants were primarily involved in teaching programs that had at least some focus on the wind industry, as shown in Figure 7.

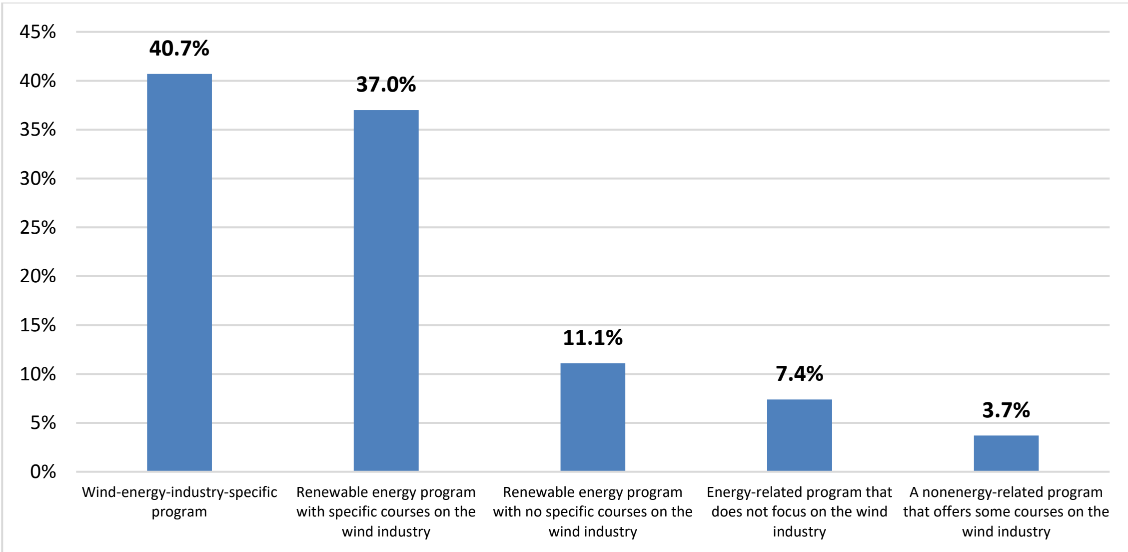


Figure 7. Program involvement with the wind energy industry (n =27)

The next section will discuss why the system dynamics model was chosen for the *National Wind Workforce Assessment: Challenges, Opportunities, and Future Needs* (McDowell et al. 2024).

3 System Dynamics Workforce Model

Workforce planning is a complex process that can be affected by both qualitative and quantitative factors. System dynamics modeling has been applied across many industries, such as healthcare and construction, to support workforce planning and policy creation due to the modeling approach's ability to help decision makers understand the behaviors of complex systems in a more holistic manner. The computer-based model "quantifies interactions and develops a time-dependent view of how a complex system behaves to help design more effective policy changes" (System Dynamics Society 2022). A system dynamics model's main goal is to analyze dynamic systems using simulation modeling based on feedback systems theory, or the ability to recognize cause and effect within a system. For this report, we developed the simulation model using VENSIM, a commonly used system dynamics modeling software. The following sections will describe why we chose this approach and how it was created through group-based modeling.

3.1 Why System Dynamics Modeling?

The *National Wind Workforce Assessment: Challenges, Opportunities, and Future Needs* (McDowell et al. 2024) was the first time a system dynamics model was used at NREL to simulate wind workforce estimations. The need for a model that can help understand the complexities of workforce planning became increasingly apparent as qualitative data collected through survey efforts indicated the presence of a wind workforce gap. Previous research efforts have highlighted the need to quantify the wind workforce gap; however, existing workforce models at NREL typically did not have this capability.

Previously, workforce projections were conducted through the Jobs and Economic Development Impact (JEDI) model using investment cost and wind capacity expansion data. The JEDI model is an Microsoft-Excel-based input-output model that "estimates the economic impacts of constructing and operating power plants, fuel production facilities, and other projects at the local level."[5] Although the JEDI model can help estimate project development and on-site labor impacts, local revenue and supply chain impacts, and other induced impacts to estimate the full-time equivalent (FTE) job demand, it does not account for the number of workers being supplied through education and training programs or transitioning into the workforce. Therefore, the JEDI model cannot quantify the potential workforce gap—the difference between the workforce needed to meet deployment and the workforce that can be supplied to meet that demand.

After conducting a literature review of workforce forecasting modeling approaches, we determined system dynamics modeling could support workforce planning by comparing the workforce supply and demand which helps to show the trends of a potential workforce gap, or the difference between supply and demand. It can also help identify delays in workforce development, such as the time it takes to go through education and training, as well as compare how demand interacts with supply, which is critical for simulating workforce gap estimation. These capabilities made system dynamics modeling the right choice for performing workforce estimation and scenario simulation for the wind workforce. This section will describe the structure of the model and the key levers considered. The following section discusses what data

[5] To learn more about the Jobs and Economic Development Impact model, visit https://www.nrel.gov/analysis/jedi/.

we used to populate the model, how we quantified the survey data, and how we simulated the scenarios.

3.1.1 Model Creation

System dynamics workforce models have been created across many industries, however, there are few being used in the U.S. wind energy industry (or other renewable energy industries), making group model building and expert review critical for model development. Group model building is a stakeholder-focused method that aims to identify root causes of a complex problem using causal loop diagrams (CLDs) (Gerritsen et al. 2020). The creation of the wind workforce model involved the team engaging with a group of workforce and modeling experts to help verify key systemic levers included in the model as identified from the previous wind workforce survey efforts.

Subsequently, the team used this expert feedback to map the system's behavior and developed a causal loop and stock-and-flow diagram for the nationally focused wind workforce model. A CLD is a circular feedback loop that links variables and displays the relationships between them. They can either be self-reinforcing (positive) feedback loops, or self-correcting (negative) feedback loops (Sterman 2000). According to systems thinking theory, linking multiple feedback loops together creates a concise narrative about the complex problem being explored (Lannon 2016); however, CLDs are rarely simulated, as they do not provide enough information to explain uncertainties. Therefore, CLDs are primarily used as an intermediate mental model step before developing the system dynamics model (Bridgeland and Zahavi 2009). For the national wind workforce assessment, the causal loop diagram linked two balancing loops together, with one of the loops representing the supply of the wind workforce and the other loop representing the demand.

Once we completed the causal loop diagram, we modeled a stock-and-flow[6] diagram in VENSIM that was based on the CLD. Stock-and-flow diagrams are used to simulate the system dynamics model in a computer software. The diagrams represent variables that are "fundamental to generating system behavior" and the associated rates that cause the stocks to change (Ventana Systems, Inc. 2023). The following sections describe how the model was structured to estimate the wind energy workforce supply, demand, and gap from 2021 to 2050. Figure 8 provides a high-level stock-and-flow diagram used for this model but does not include levers that influence the displayed stocks.

[6] Stock and flow diagrams are composed of stocks and flows. A stock is the quantity of something in the system (e.g. students), while a flow is the rate of change of movement between stocks.
https://www.vensim.com/documentation/usr05.html

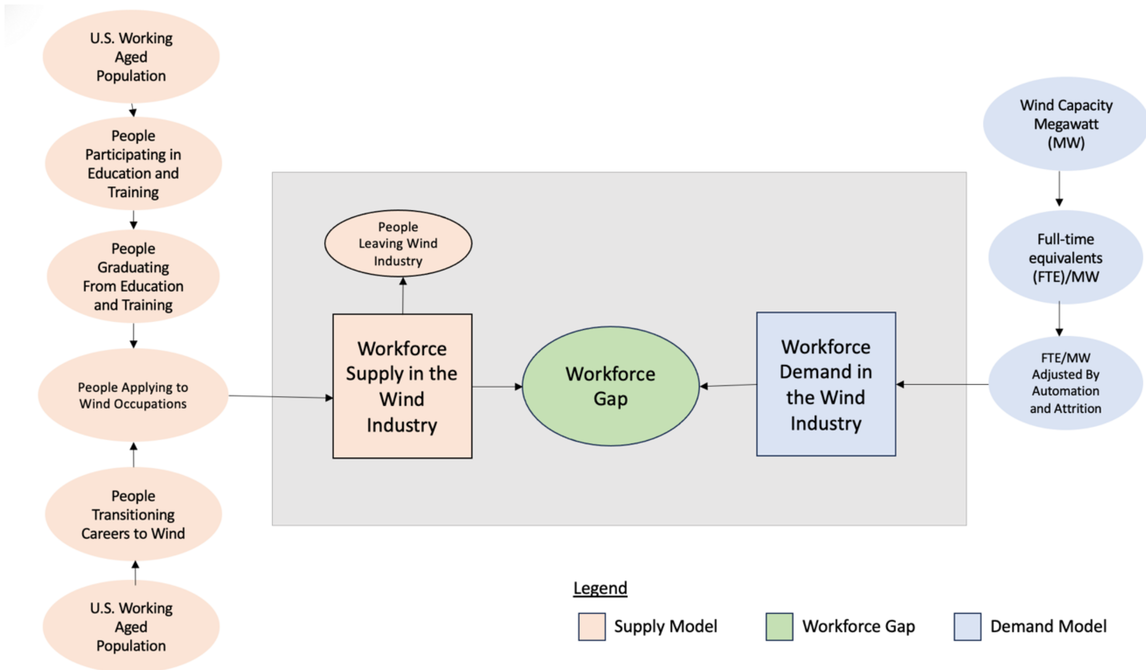


Figure 8. A high-level stock-and-flow diagram of the wind energy workforce system dynamics model

3.1.2 Supply Model for the Wind Workforce

To estimate the supply of the U.S. wind workforce on a national level through 2050, we considered the population of working aged U.S. citizens, number of graduates from education and training programs, number of people transitioning into renewable energy, and the number of people being hired into the wind energy industry. Figure 9 shows the subsections of the supply model and the input and output that results from each subsection.

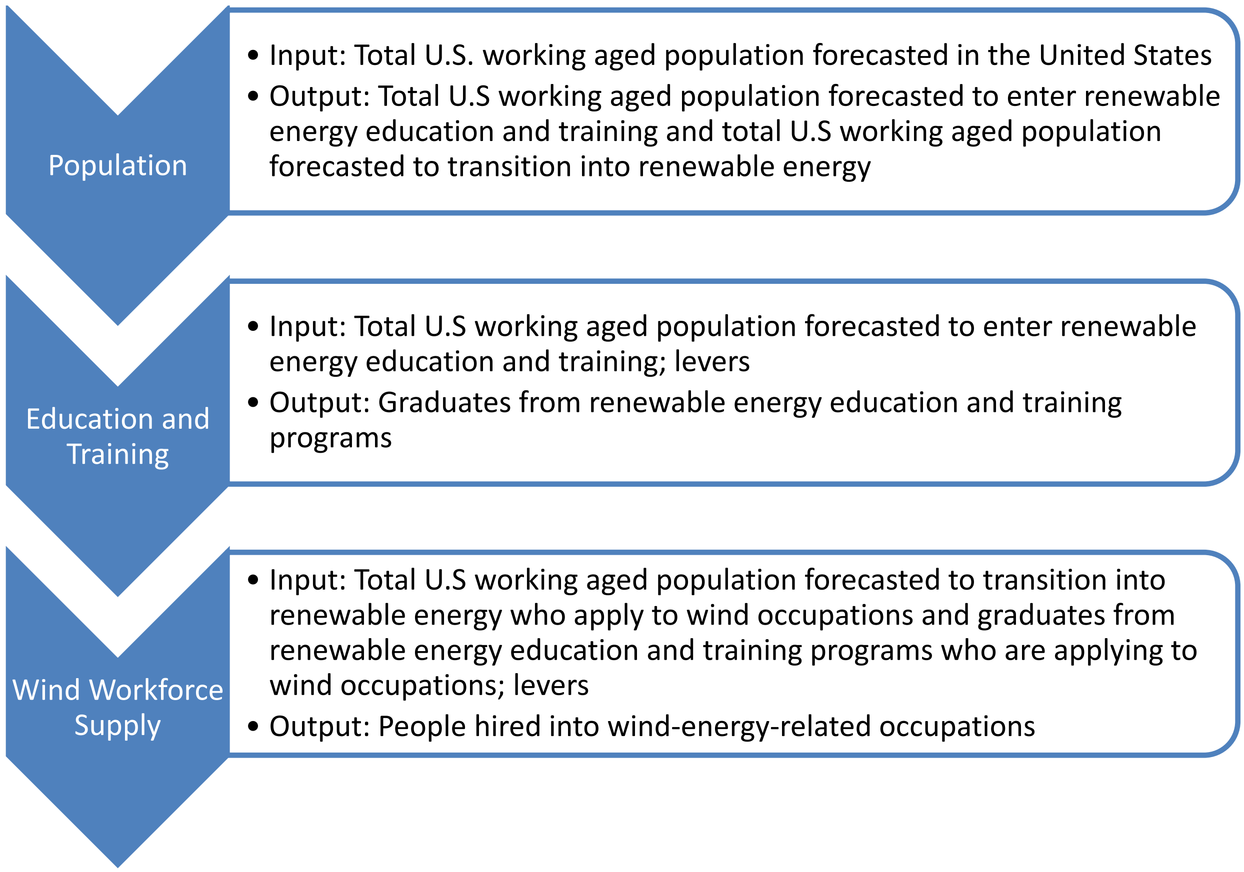


Figure 9. High-level inputs and outputs of each subsection within the wind workforce supply model

The initial input for the supply side of the model is the U.S working aged population estimation from 2021–2050 from the U.S. Census Bureau (2023). The U.S. working aged population input is then multiplied by the percentage of people who work in renewable energy and other industries to separate the stock into two groups. The people who are going to work in renewable energy are then separated further into two groups:

- A group that requires education or training to reach a desired level of qualification
- A group that is transitioning directly into the renewable energy industry without additional formal training or education.

The number of people who are going into education and training programs is affected by acceptance, enrollment, and dropout rates that are controlled by key impact levers determined through the 2022 survey effort (Table 2). The people who go into the education and training pipeline are further divided by participation in a 4-year degree, 2-year degree or certification, or apprenticeship program. These training pipelines are associated with respective delays of 4 years, 2 years, and 3 years to account for the average time it takes between enrollment and graduation. Table 2 shows the key levers that control the rates that are applied to adjust the supply for the 4-year degree programs, 2-year degree or certificate programs, and apprenticeship programs.

Table 2. Key Levers That Affect the Education and Training Program Pipeline

Key Rates	Key Levers as Identified in the Survey Effort
% Applying into Education and Training Programs	Marketing intensity
	Economic drivers
	Societal drivers
Acceptance Rate into Education and Training Programs	Student to teacher ratio
	Funding
	Infrastructure availability
	Curriculum changes
Enrollment Rate into Education and Training Programs	Not applicable (N/A)
Dropout Rate into Education and Training Programs	N/A

The education and training programs are assumed to be for renewable energy, and are not specific to the wind industry, therefore, the number of graduates from those programs are affected by the rate at which individuals apply to wind-related jobs on average. The education and training programs were not wind-specific to help account for application competition among other industries and wind. The application rate is changed by key levers that adjust the attractiveness of applying to jobs in the wind industry, which affects the number of people applying to wind-related jobs. Table 3 shows the key levers that determine the job application rate of renewable energy education and training graduates to the wind industry as indicated by the survey effort. The key levers are also applied to wind industry job seekers who transitioned into renewable energy without having to go through a formal training or education program.

Table 3. Key Levers That Affect the Stock of Applicants to Wind-Energy-Related Jobs

Key Rates	Key Levers as Identified in the Survey
% of Applicants to Wind Who Are Graduates of Renewable-Energy-Related Degree Programs	Labor wages
	Location of jobs
	Job stability
	Awareness of opportunity
	Job availability
	DOE program participation

The individuals who apply to the wind industry are entered into an application pool, which is adjusted by a hiring rate and accounted for in the "Workforce Supply in the Wind Industry" stock (Figure 8). The people who work in the wind industry are then adjusted by two rates: one that accounts for people leaving the industry and another that withdraws workers who are double counted as both students and wind industry employees. The process and levers described earlier ultimately estimate the number of employees in the wind industry for any given year between 2021 and 2050.

3.1.3 Demand Model for the Wind Workforce

To estimate the demand of the workforce through 2050, we considered multiple factors including:

- Annual deployment capacity of land-based and offshore wind in megawatts (MW)
- FTE/MW installed
- Automation's impact on workforce demand
- Manufacturing content produced domestically.

The annual wind deployment capacity (MW) is multiplied by the FTE/MW installed factor to convert FTE/MW installed to FTE jobs. We derived this FTE estimate from current wind employment according to the *U.S. Energy and Employment Report* (DOE 2022a) and is therefore based on the current development and supply chain for the U.S. wind industry in 2022. The FTE output was calculated for multiple wind industry sectors related to the report including professional services, wholesale trade, manufacturing, construction, utilities, and operations (DOE 2022a). The FTE for each wind industry sector is then adjusted to account for automated processes affecting the workforce demand. Additionally, the wind industry segment for manufacturing is also adjusted by a lever that controls the percentage of content produced domestically. However, this percentage is assumed to only affect the manufacturing industry sector. Once the FTE demand is determined for each industry sector, the results are aggregated to show a complete workforce demand number. The workforce demand is then subtracted by the workforce supply to calculate the workforce gap estimation.

4 System Dynamics Workforce Model: Data, Validation, and Results

The system dynamics model can be used to explore how scenarios may affect the wind workforce trends for supply, demand, and gaps. The results of the system dynamics wind workforce model are dependent on survey and data collection efforts. The model output is not meant to be a conclusive projection of the workforce through 2050. However, it is intended to be one of the tools that can help inform decision-making as an adequate (numerically) and properly trained wind energy workforce is developed. This model does not account for the economic impacts of developing the workforce and does not produce results on an occupational level.

To populate the system dynamics model with data, we used various sources, such as the Bureau of Labor Statistics, U.S. Department of Education, *United States Energy and Employment Report 2022*, NREL 2022 Standard Scenarios, and the 2022 wind energy workforce survey effort described above. Data from these sources were used as inputs for the model to simulate the baseline workforce estimation. Key levers were then adjusted to evaluate how the wind workforce supply, wind workforce demand, and wind workforce gap would shift based on changes in the perception of the wind industry by job seekers or impacts of some influential policies relevant to wind.

4.1 Data Population

While many quantitative sources were used to set initial inputs into the model, the data leveraged within the key levers (Table 2 and 3) related to perception or influence were collected through the 2022 wind energy workforce survey effort. Appendix B shows a list of the variables and their data sources.

Workforce development is largely dependent on the behavior of the people within the system; however, behavioral data are difficult to quantify, and therefore use in numerical models. To overcome this challenge, the workforce model aimed to include behavioral survey data by using weighted averages in conjunction with survey data that used Likert scales. A Likert scale is "a rating system, used in questionnaires, that is designed to measure people's attitudes, opinions, or perceptions"[7]. By taking the number of votes for each category of the Likert scale within the applicable survey question and applying a weighted average to the number of votes (Eq. 1), we were able to quantify the data. Those values were then input into the system dynamics workforce estimation model as a baseline input.

$$W = \frac{(Total\ \#\ of\ Respondents\ Category\ 1 * weight\ 1) + (Total\ \#\ of\ Respondents\ Category\ 2 * weight\ 2) + \cdots}{Sum\ of\ the\ Weights} \quad (1)$$

The key levers of the model were bound between 0 and 1, with 0 indicating a decrease in the associated rate and 1 indicating an increase in the associated rate. If a key lever of the model was adjusted from the baseline input toward 0, the rate that the lever corresponds to decreased from the initial input level. For example, if the perception lever associated with labor wages for

[7] Likert scale. 2013. Encyclopedia Britannica. https://www.britannica.com/topic/Likert-Scale

graduates of 2-year degree programs is move toward 0 or is indicated to be "worse than average" when compared to other occupations, the model will estimate that fewer graduates will be applying to wind industry jobs. The 0 to 1 scale was applied to all associated key levers.

4.2 Validation

After the model was populated with data, it underwent many iterations of verification, validation, and revision. At different stages of creation, the system dynamics model was tested and reviewed by both the modelers and independent experts. In addition to step-by-step verification, a variety of tests were used to build confidence in the model's ability to reflect reality. However, there is no single test to validate a system dynamics model, but confidence can grow as more validation tests are passed. Furthermore, typical statistical tests are not always appropriate for system dynamics models because of the nature of simulation modeling, and validation is based on establishing confidence in the usefulness of a model (Senge and Forrester 1980). In system dynamics modeling, the soundness and usefulness of the model depends heavily on aligning with empirical reality and the intended audience for the model results. Therefore, validation begins as the model builder accumulates confidence that the model "behaves plausibly and generates problem symptoms or modes of behavior seen in reality" (Senge and Forrester 1980).

There are traditionally three verification types within system dynamics (Schwaninger and Groesser 2009):

- Tests of model-related context
- Tests of model structure
- Tests of model behavior

Within each verification type are additional tests that can be performed to build confidence in the validity of the model. Not all 12 of the tests referenced in the *System Dynamics Modeling: Validation for Quality Assurance* (Schwaninger and Groesser 2009) report were run. The ones that were chosen were based on a prioritization list within the *Tests for Building Confidence in System Dynamics Models* (Forrester 1980) report.

The wind workforce system dynamics model passed 7 of the 12 tests that are referenced in the System *Dynamics Modeling: Validation for Quality Assurance* (Schwaninger and Groesser 2009) report including the:

- Structure examination test
- Parameter examination test
- Direct extreme condition test
- Dimensional consistency test
- Boundary adequacy policy test
- Symptom generation test
- Pattern anticipation test.

As part of the symptom generation test, we compared the system dynamics model outputs to historical data. For consistency, the historical data were sourced from previous *United States Energy and Employment Reports* starting in 2015. Additionally, the actual installed U.S. wind capacity was used to propagate the demand side of the model up until 2022 (International Renewable Energy Agency 2022). Figure 10 shows what the *United States Energy and*

Employment Report estimated as the current workforce from 2015 to 2022 (red) in comparison to the model estimates from 2015 to 2050 (blue) and from 2021 to 2050 (green). The 2015 to 2050 estimation uses historical inputs for the U.S. working age population, initial workforce supply, and wind capacity deployment; however, all other inputs are consistent with the 2021 to 2050 baseline data inputs.

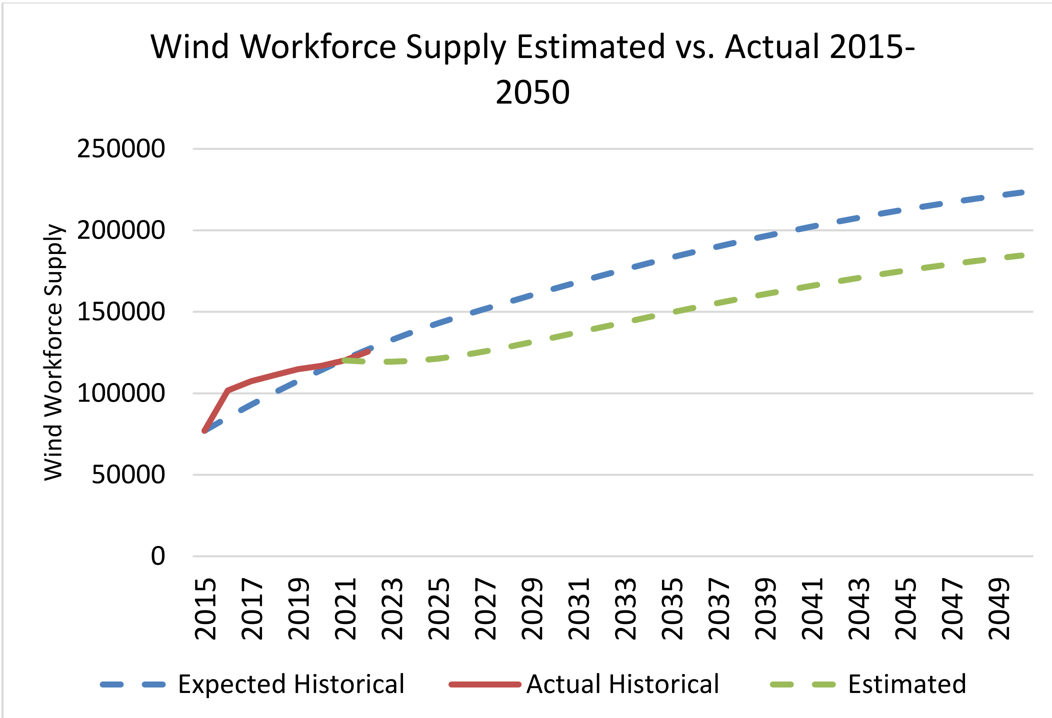


Figure 10. Historical comparison of the system dynamics model outputs vs. the *United States Energy and Employment Report* estimations

As more information on the wind workforce is understood, revisions to the system dynamics model can be made to increasingly build confidence in the method for estimating the wind workforce supply, demand, and gap. More information on limitations of the model, and specific areas where confidence can be built is in Section 5: Limitations of the Model and Section 6: Future Work.

4.3 Scenario Results

Once the model was populated with data, we ran three scenarios in addition to the business as usual (BAU) scenario to explore actions that could be taken to mitigate the wind workforce gap. The three scenarios included the:

- Renewable Energy Education and Training Programs scenario (Scenario 1)
- Applicants to Wind Industry Jobs scenario (Scenario 2)
- Inflation Reduction Act scenario (Scenario 3).

More information on the assumptions and results of the scenarios can be found in the *National Wind Workforce Assessment: Challenges, Opportunities, and Future Needs* (McDowell et al. 2024) report. The BAU scenario, Scenario 1, Scenario 2, and Scenario 3 are defined as follows:

- The BAU scenario provides the workforce supply, demand, and gap estimations most likely to occur if current assumptions and data remain constant.
- The Renewable Energy Education and Training Programs scenario (Scenario 1) looks at how changing the impact of key factors identified through the wind energy workforce survey effort (e.g., marketing intensity, economic drivers, and societal drivers) affects how many people apply for education or training programs. Additionally, Scenario 1 tests how positively or negatively impacting education and training programs' student/teacher ratio, funding levels, infrastructure availability, and curriculum affect acceptance rates into education and training programs.
- The Applicants to Wind Industry Jobs scenario (Scenario 2) evaluates how changing the perception job seekers have regarding labor wages, job stability, and job location will affect the number of applicants to wind industry jobs.
- Inflation Reduction Act scenario (Scenario 3) tests how workforce-related factors such as apprenticeship requirements, prevailing wage, and domestic content incentives affect workforce supply estimations.

4.3.1 BAU Scenario

From the baseline data, it was indicated that the wind industry supply is set to increase through 2050; however, it is not at the rate needed to meet 2030 or 2050 wind workforce demand estimates. Figure 11 shows the estimates from 2021 through 2050. The model estimates that the total wind workforce supply in 2030 will be approximately 134,000 workers, whereas the total workforce demand is estimated to be 258,000 workers. This finding indicates that there is a deficit of around 125,000 workers for offshore and land-based wind energy. However, as described earlier, these numbers are highly dependent on the assumption of the data gathered through the 2022 wind energy workforce survey effort and do not factor in the increasing demand for workers from other renewable energy source that can also affect the gap in future years. There are many complex labor marker factors that can influence this estimate but were not included into the modeled system. Therefore, these numbers should be used as a high-level estimate of scale as opposed to a point projection of future jobs (McDowell et al. 2024). For more information on model limitations please reference Section 5: Limitations of the Model.

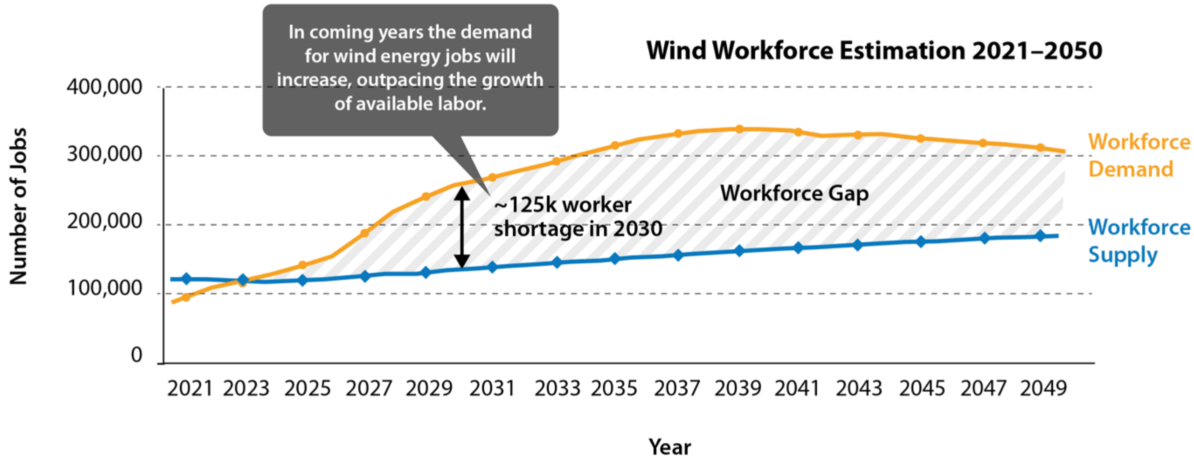


Figure 11. Workforce development estimations that show worker demand, worker supply, and the magnitude of a potential gap in workforce need under business-as-usual assumptions. ***Image created by John Frenzl, NREL***

4.3.2 Scenario 1: Renewable Energy Education and Training Programs

To test Scenario 1, the key levers that affect the percentage of people applying for renewable energy education and training programs, and the percentage of people being accepted into renewable energy education and training programs were adjusted incrementally between 0 and 1 from the baseline inputs. We developed four simulations to provide a range for potential workforce increases and decreases based on the possible actions that correspond with moving the levers in a positive or negative direction from the BAU scenario. The simulations include:

- Minimal influence. Decreasing the levers related to the application or acceptance rate by 100% from the baseline; the lever is moved to 0.
- Low influence. Decreasing the levers related to the application or acceptance rate by 50% from the baseline
- BAU. Calculated based on the wind energy workforce survey data, as described in Section 4.1
- High influence. Increasing the levers related to the application or acceptance rate by 50% from the baseline
- Maximum influence. Increasing the levers related to the application or acceptance rate by 100% from the baseline. The lever is moved to 1.

It was assumed in Scenario 1 that the effects of the lever adjustments would be realized over 30 years, causing an approximate 18,700 worker supply difference between the minimum and maximum scenarios by 2050 (Figure 12).

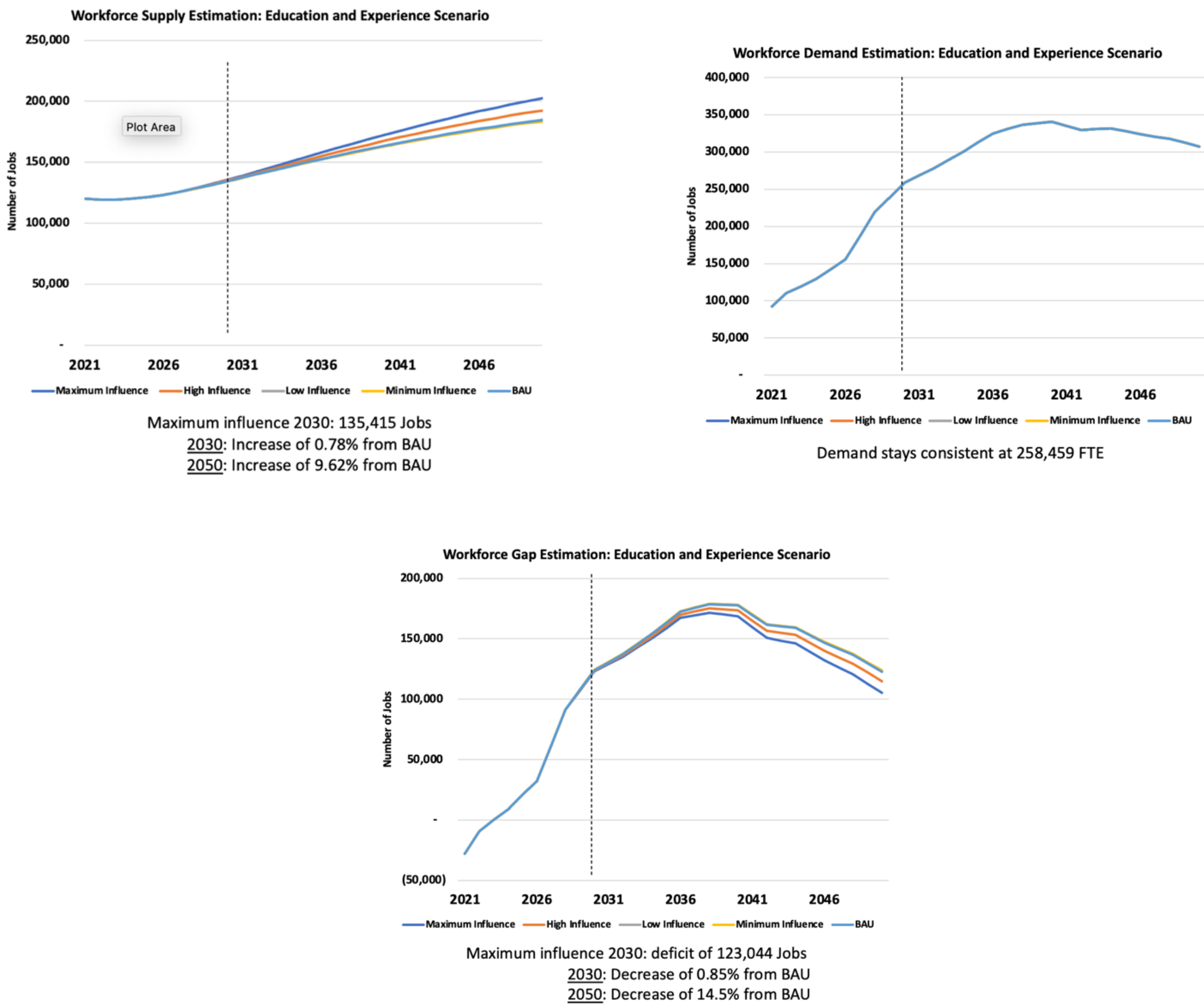


Figure 12. Workforce supply, workforce gap, and workforce demand changes as affected by the renewable energy education and training program's 30-year scenario

If this same scenario is simulated, but the full effects of the lever adjustments are realized over 10 years instead of 30 years, then the approximate difference in workers between the minimum and maximum scenarios is approximately 26,600 workers by 2050 (Figure 13). The increase between the minimum and maximum scenarios indicates that the consequences of the lever adjustments are continuously realized throughout the time frame of the model.

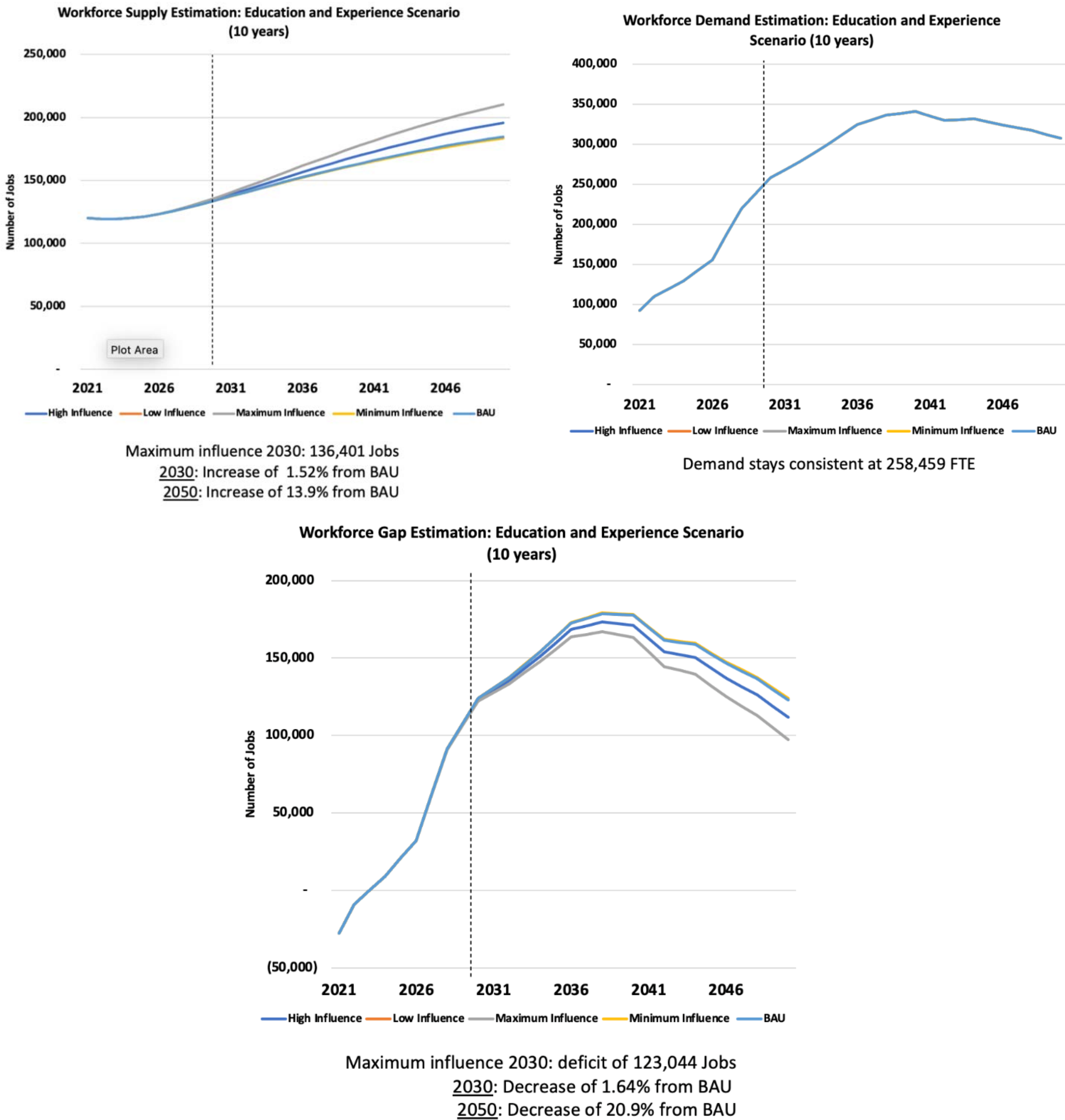


Figure 13. Workforce supply, workforce gap, and workforce demand changes as affected by the renewable energy education and training program's 10-year scenario

4.3.3 Scenario 2: Applicants to Wind Industry Jobs

To test Scenario 2, the key levers that affect the percentage of applicants to wind from graduates of renewable-energy-related degree programs were adjusted incrementally between 0 and 1 from the baseline input. We developed five simulations to present a range for potential workforce increases and decreases based on the possible actions that correspond with moving the levers in a positive or negative direction from the BAU scenario. The simulations include:

- Minimal influence. Decreasing the levers related to the application rate to wind energy industry jobs by 100% from the baseline; the lever is moved to 0
- Low influence. Decreasing the levers related to the application rate to wind energy industry jobs by 50% from the baseline
- BAU. Calculated based on wind energy workforce survey data as described in Section 4.1.
- High influence. Increasing the levers related to the application rate to wind energy industry jobs by 50% from the baseline
- Maximum influence. Increasing the levers related to the application rate to wind energy industry jobs by 100% from the baseline. The lever is moved to 1.

We assumed in this scenario that the effects of the lever adjustments would be realized over 10 years, causing an approximate 55,700 worker difference between the minimum and maximum scenarios by 2050 (Figure 14).

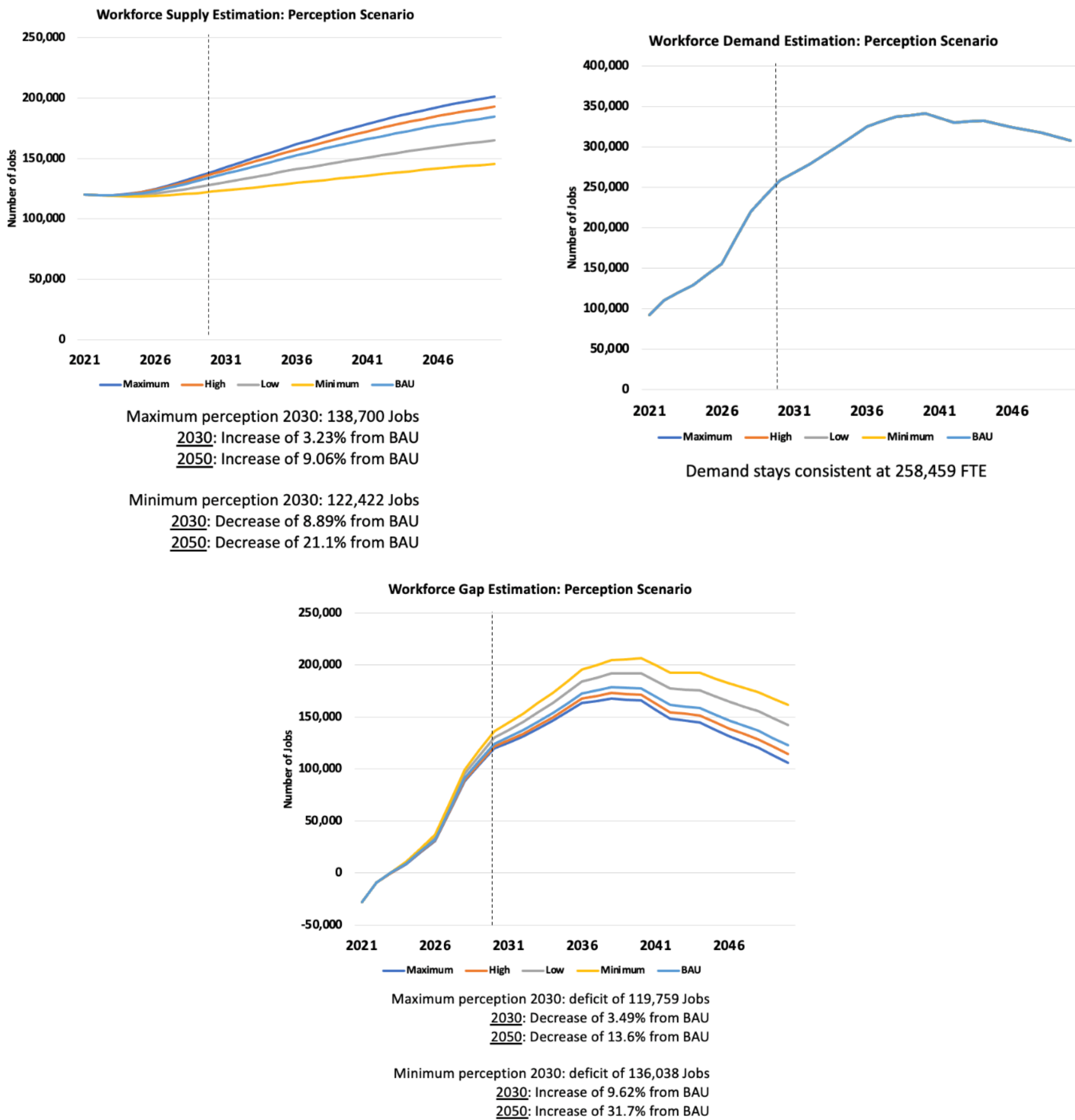


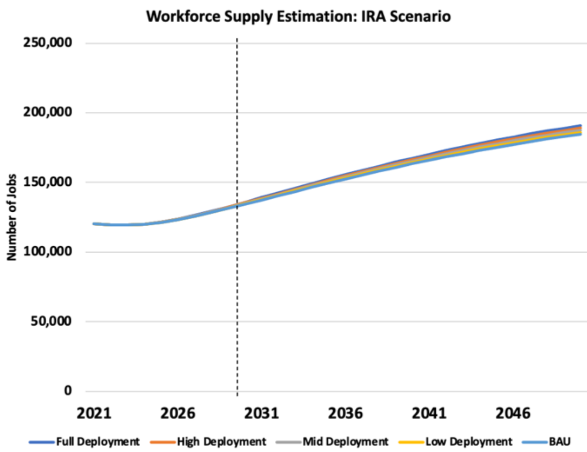
Figure 14. Workforce supply, workforce gap, and workforce demand changes as affected by the applicants to wind industry jobs scenario

4.3.4 Scenario 3: Inflation Reduction Act

To test Scenario 3, levers that affect apprenticeship utilization requirements, labor wages, and domestic content incentives were incrementally adjusted between the baseline input and 1. We developed five simulations to present a range for potential workforce increases and decreases based on the possible actions that correspond with moving the levers in a positive or negative direction from the BAU scenario. The BAU scenario was the lowest scenario because it was assumed that the effects of the Inflation Reduction Act (IRA) would only increase the number of workers entering the wind energy industry and the IRA's impact on workforce supply was not evaluated through the 2022 survey effort. The simulations include:

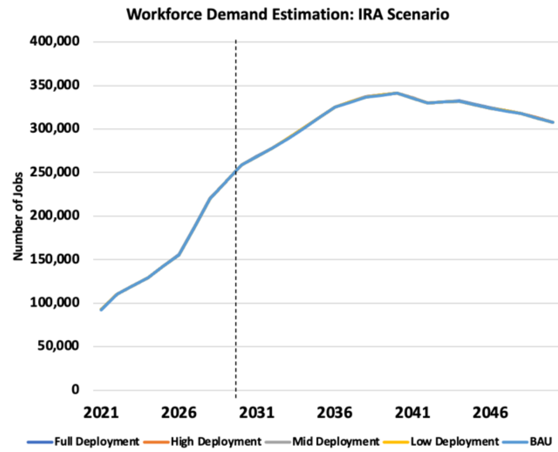
- BAU. Calculated based on survey data, as described in Section 4.1
- Low deployment. Increasing the levers related to the IRA by 25% from the baseline
- Mid deployment. Increasing the levers related to the IRA by 50% from the baseline
- High deployment. Increasing the levers related to the IRA by 75% from the baseline
- Full deployment. Increasing the levers related to the IRA by 100% from the baseline.

We assumed in Scenario 3 that the effects of the lever adjustments would be realized over 10 years to match the time frame of when most of the incentives start expiring. We also assumed that the IRA’s effects on the demand side of the model were already accounted for due to the assumption within the NREL 2022 Standards Scenario Mid-case with nascent technology and current policy (Gagnon et al. 2022). More information about the exact assumptions can be found in the *National Wind Workforce Assessment: Challenges, Opportunities, and Future Needs* (McDowell et al. 2024). As a result, this scenario resulted in an approximate 6,100 worker difference between the minimum and maximum workforce supply scenarios by 2050 (Figure 15).



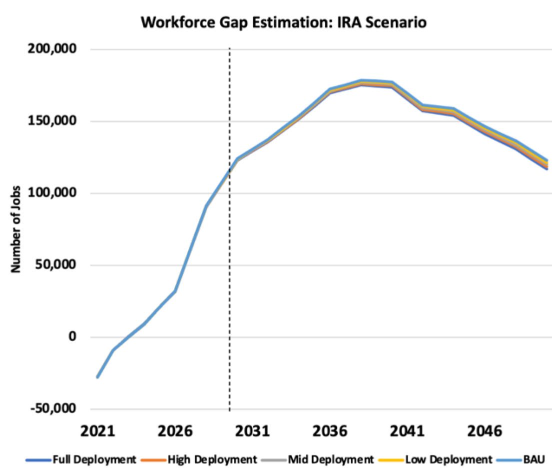
Full deployment 2030: 135,761 Jobs
2030: Increase of 1.04% from BAU
2050: Increase of 3.35% from BAU

Low deployment 2030: 134,701 Jobs
2030: Increase of 0.25% from BAU
2050: Increase of 0.77% from BAU



Full deployment 2030: 258,770 Jobs
2030: Increase of 0.12% from BAU
2050: Increase of 0.10% from BAU

Low deployment 2030: 258,539 Jobs
2030: Increase of 0.03% from BAU
2050: Increase of 0.03% from BAU



Full deployment 2030: deficit of 123,008 Jobs
2030: Increase of 0.88% from BAU
2050: Increase of 4.78% from BAU

Low deployment 2030: deficit of 123,837 Jobs
2030: Increase of 0.21% from BAU
2050: Increase of 1.09% from BAU

Figure 15. Workforce supply, workforce gap, and workforce demand changes as affected by the Inflation Reduction Act scenario

5 Limitations of the Model

Two of the benefits to using systems dynamics models are their ability to display dynamic feedback loops and incorporate time delays. Due to limited data availability and resource constraints during the initial model development, there is opportunity to improve the robustness of the dynamic feedback loops and associated delays within future model development. Figure 16 displays the causal loop diagram that was developed for this model. As shown in the CLD, the authors recognize that hiring rates and job availability will be influenced by wind energy deployment demand; however, there are many uncertainties on how factors like supply chain delays will affect when the workforce is needed and how it will affect the number of job openings. Due to the uncertainty, and lack of data on how hiring rates are influenced by wind energy deployment demand as well as workforce demands for other energy technologies, the hiring rate was treated as exogenous to the model and kept at a constant rate. The authors recognize this as a limitation to the usefulness of the model and are working to gather data on how to model this dynamic loop. Furthermore, other dynamic loops could also be expanded upon through further development of the model, specifically how the key levers as identified through the survey effort interact with one another.

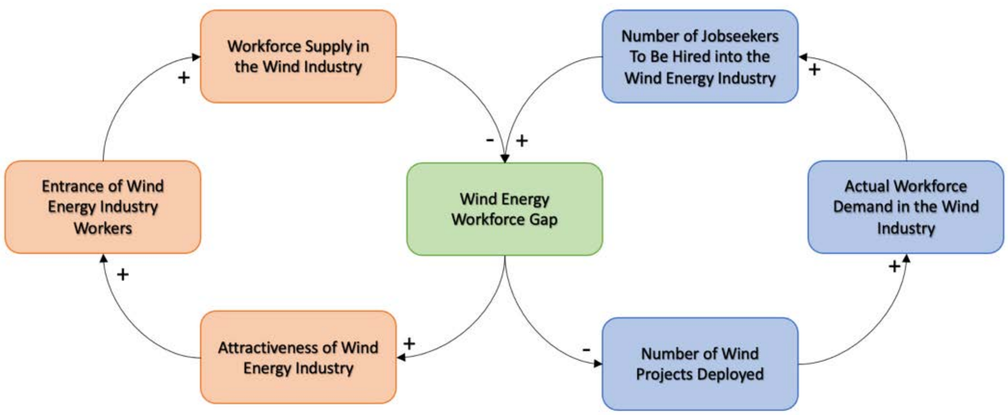


Figure 16. Causal loop diagram for system dynamics wind workforce model creation

The estimations that have been produced through the system dynamics model are not to be used as an exact forecast but were intended to be used as an indication of wind energy workforce trends under different scenarios and with specific assumptions. The outputs of the model are highly dependent on survey results, which have inherent bias as described in previous sections.

This version of the model was the first iteration of a system dynamics model for wind energy workforce and will need to be continually refined. Further research will evaluate how the system dynamics model methodology can be improved in the future.

6 Future Work

This report documents the first version of a system dynamics model that we used to estimate the U.S. wind energy workforce needs and conduct a sensitivity analysis of actions that influence workforce supply and demand. We chose the system dynamics model methodology because of its ability to add or modify initial inputs, integrate new levers, and map workforce-development-related stock and flows. During model development, we identified several areas for future capability expansion and model improvements. Some of the future model updates could include:

- **Building out occupational detail**. The wind energy industry needs many worker types with diverse education, experience, and skills. The demand side of the model provides estimates at the industry sector level. The supply side groups occupations at the apprenticeship, 2-year, and 4-year education level. Incorporating a wind occupational list, including inputs with the magnitude of jobs, would allow the system dynamics model to pair supply and demand at the occupational level.
- **Connecting modeling efforts across clean energy industries**. The system dynamics model estimates wind workforce needs: however clean energy jobs across technologies are expected to grow. Industries that overlap in the types of workers and skillsets required could allow workers to transition between technologies. Therefore, expanding the system dynamics model to include other clean energy technologies and industries with transferrable skills would provide workforce trends for all clean energy sectors, helping to understand the clean job demand over time, and provide insight into how to train a clean energy workforce that can support not only wind energy, but all clean energy and energy efficiency technologies.
- **Expanding supply stock and flows**. Education and training programs can be provided by universities, community colleges, labor unions, and industry employers. The system dynamics model currently aggregates these programs into apprenticeship, 2-year, and 4-year education levels as well as incorporates a high-level transition of workers from other industries to the wind energy industry. Future efforts could be made to better align this supply-side flow to the many pathways for education and training. Inputs could also be refined to be more training-program specific, such as collecting more information on the number of students graduating from programs and the efficacy of programs in developing the knowledge, skills and abilities required to perform the necessary jobs.
- **Collecting additional qualitative data for multiple technologies**. The system dynamics model levers are baseline inputs enabled by an in-depth survey of many stakeholder groups. Additional data collection over time would allow for continually updating the gap assessment to reflect current industry trends and new questions to add inputs, validate key levers, and gather new data on priority research questions. Moreover, the current survey efforts are specific to the wind energy industry, so to apply the model to other clean energy technologies would require technology-specific survey efforts.

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Appendix. Survey 2022

Data Sources Supply and Demand

Table A-1. Supply-Side Variables and Data Sources

Variable/Lever	Data Source
Working Aged U.S. Population (15–64)	U.S. Census Bureau (2023)
Percentage of People Going into Renewable Energy	U.S. Department of Energy (DOE) (2022a)
Percentage of People Going into Renewable-Energy-Related Education and Training	Stefek et al. (2022)
Marketing Intensity	Educators Survey (2022)
Economic Drivers	Educators Survey (2022)
Societal Drivers	Educators Survey (2022)
Initial Percentage of People Applying for 2-Year Education and Training Programs	Stefek et al. (2022)
Initial Percentage of People Applying for 4-Year Education and Training Programs	Stefek et al. (2022)
Initial Percentage of People Applying for Apprenticeships	DOE (2022a)
Acceptance Rate	National Center for Education Statistics (2021)
Student-to-Teacher Ratio	Educators Survey (2022)
Funding	Educators Survey (2022)
Infrastructure Availability	Educators Survey (2022)
Curriculum Changes	Educators Survey (2022)
Enrollment Rate	Educators Survey (2022)
Dropout Rate	Educators Survey (2022)
Percentage of People Applying into Wind from Education and Training Programs	Stefek et al. (2022)
Labor Wages Perception	Student Survey (2022)
Location Perception	Student Survey (2022)
Job Stability Perception	Student Survey (2022)
Awareness	Student Survey (2022)

Variable/Lever	Data Source
Job Availability	Student Survey (2022)
U.S. Department of Energy Programs Perception	Student Survey (2022)
Collegiate Wind Competition Perception	Student Survey (2022)
Kid Wind Perception	Student Survey (2022)
North American Wind Energy Academy Perception	Student Survey (2022)
National Energy Education Development Perception	Student Survey (2022)
Percentage of People in Education or Training and Working	Student Survey (2022)
Hiring Rate	Georgia Institute of Technology Career Center (2023)
Attrition Rate	U.S. Bureau of Labor Statistics (2021)

Table A-2. Demand-Side Variables and Data Sources

Variable/Lever	Data Source
Full-Time Equivalent/Megawatt	DOE (2022a)
Wind Capacity Estimations	Gagnon et al. (2022)
Percentage of Domestic Content	DOE (2022b)
Percent Change in Automation	International Federation of Robotics (2021)
Decrease of Jobs Due to Automation	Acemoglu and Restrepo (2020)

System Dynamics Model

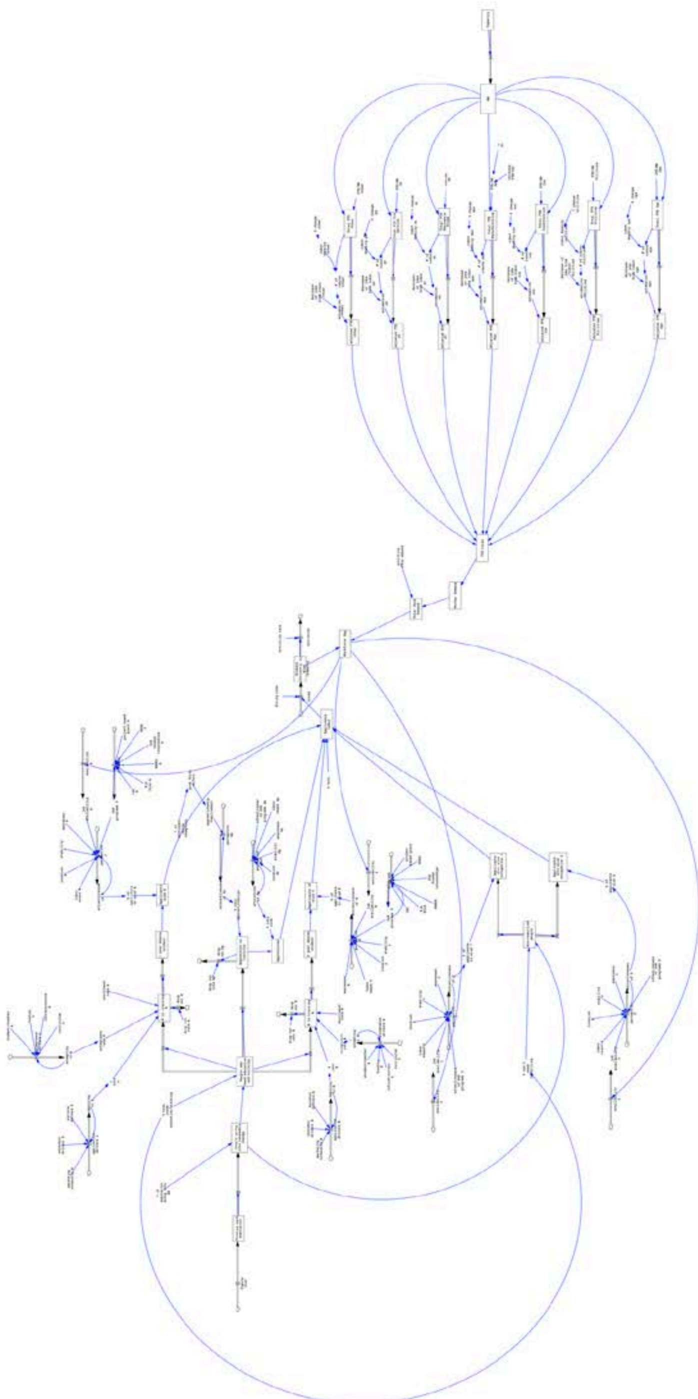

Figure A-1. Full image of the system dynamics model within VENSIM

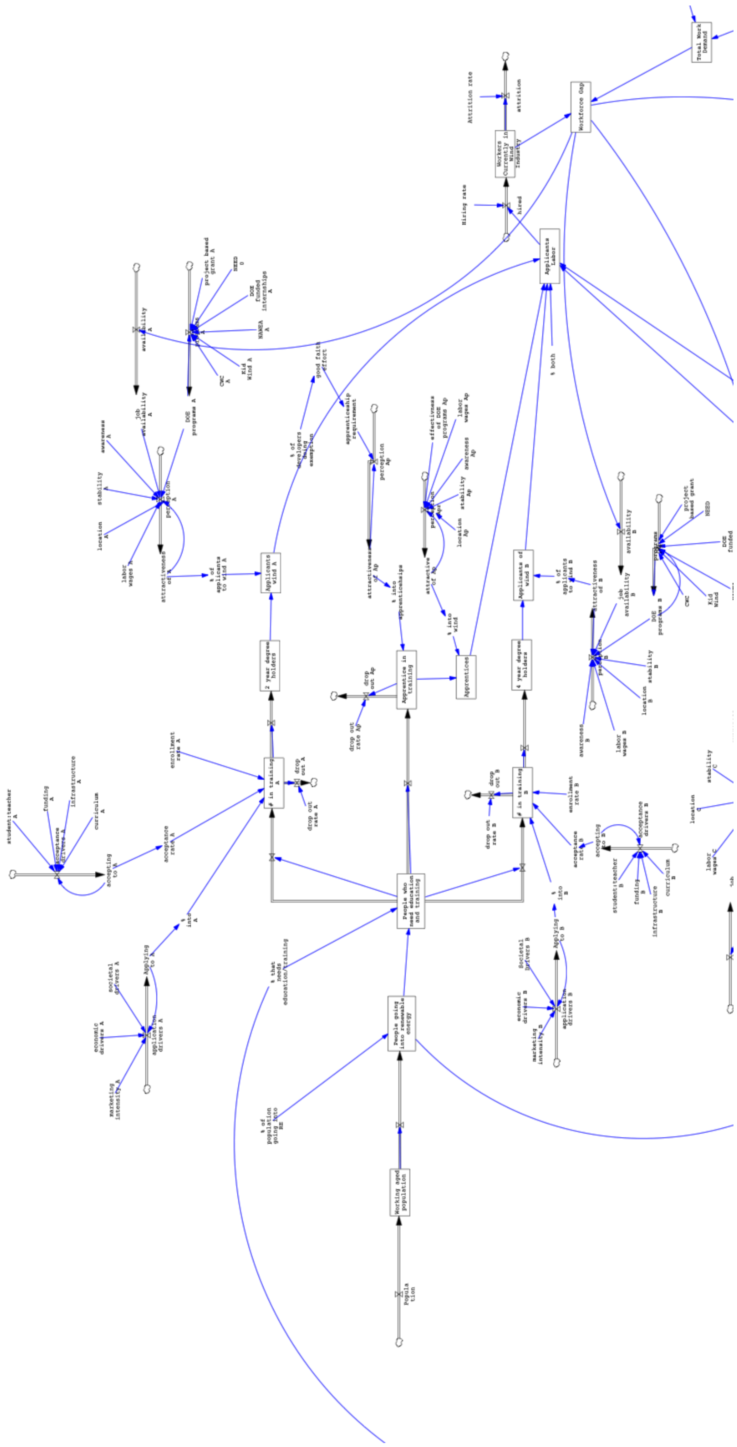

Figure A-2. Top image of the system dynamics model supply side within VENSIM

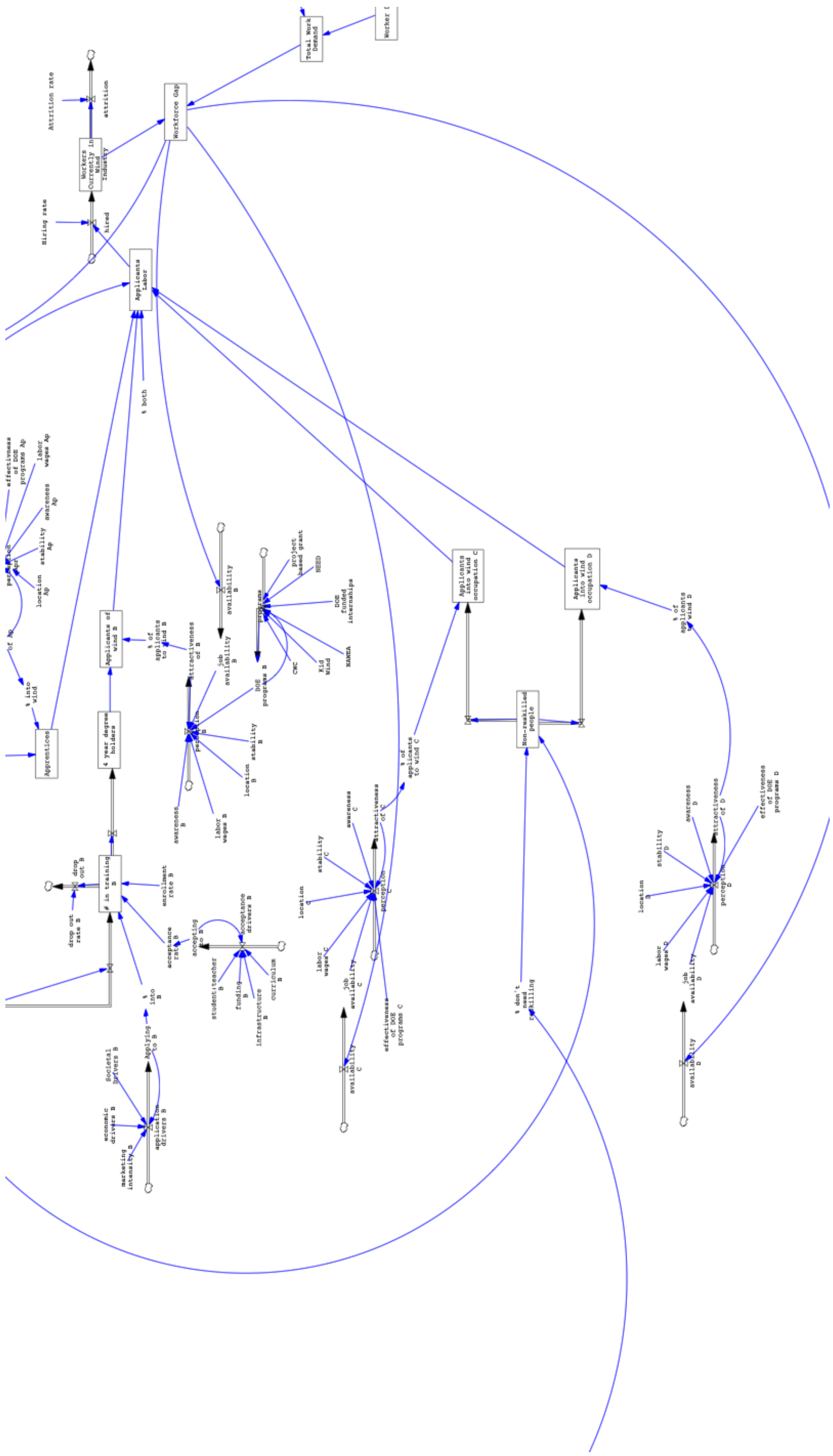

Figure A-3. Bottom image of the system dynamics model supply side within VENSIM

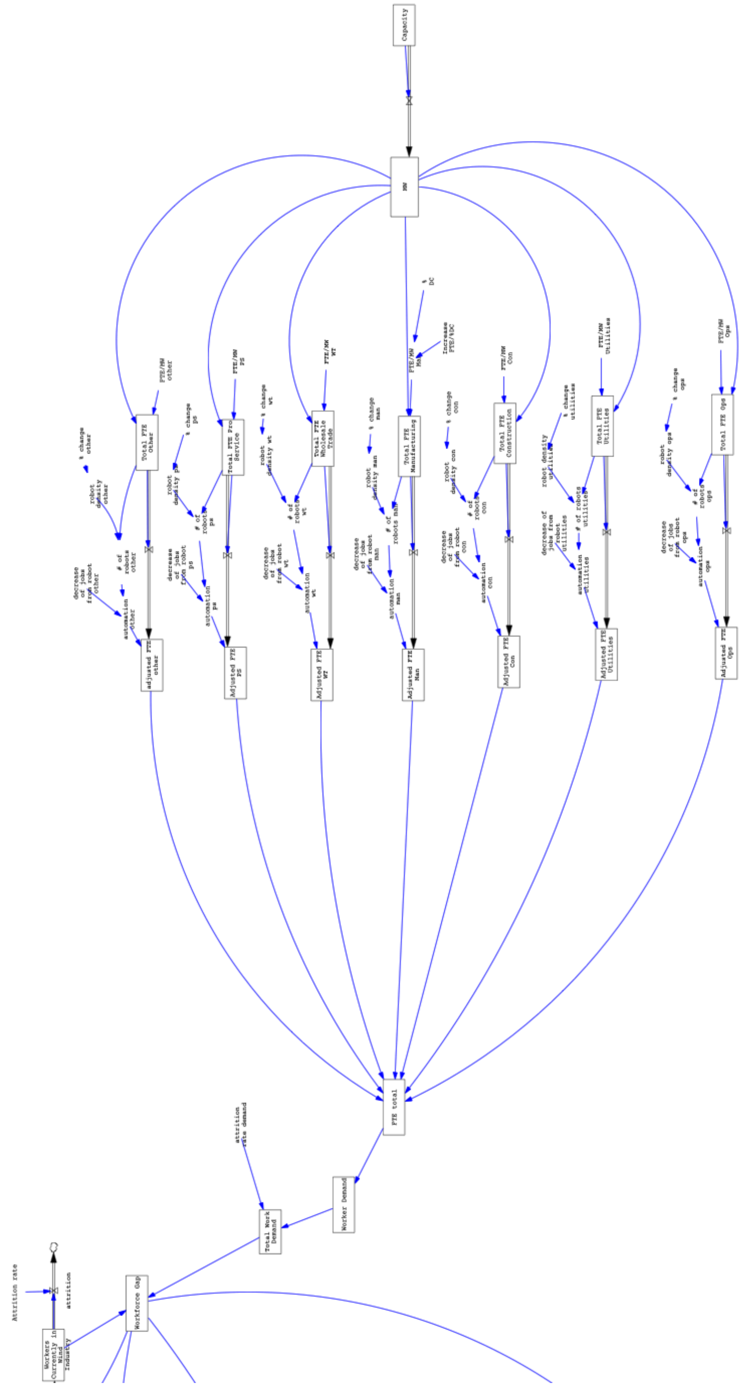

Figure A-4. Bottom image of the system dynamics model supply side within VENSIM