Innovative Open-Source Energy Software to Drive and Enable Energy Savings and Process Optimization

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ABSTRACT

U.S. Department of Energy (DOE) energy system-analysis software tools have been used for years helping to identify over 170 TBTU/year of energy savings through the Save Energy Now "Energy Savings Assessment" and Better Plants "In-Plant Training" Programs. While most of the fundamental energy savings opportunities do not evolve much with time, computer technology never stops, leaving most of these software tools inoperable on modern computers.

This has sparked an initiative to revitalize the DOE energy system analysis tools into a new, open-source, integrated software tool suite - MEASUR. Designed for industrial energy coordinators, engineers, utility-program implementers and individuals who are interested in improving system efficiency, MEASUR can aide users in identifying, assessing, and quantifying energy savings opportunities within pump, fan, process heating, steam, motors, and compressed air systems. In addition, the software contains over 40 equipment and property calculators for simple energy-related calculations and analyses.

This paper will present a results comparison for each energy-consuming system using data from past DOE-sponsored energy assessments (to establish the accuracy of the savings algorithms) to validate and verify the accuracy of the energy and cost savings calculated by MEASUR. Additionally, an example highlighting 3rd-party development of the tool's open-source framework into real-time sensor systems and efficiency-optimization will be presented.

List of Abbreviations

AMO	Advanced Manufacturing Office
DOE	U.S. Department of Energy
ESA	Energy Savings Assessment
FSAT	Fan System Assessment Tool
IAC	Industrial Assessment Center
InPLT	In Plant Training
MEASUR	Manufacturing Energy Assessment Software for Utility Reduction
ORNL	Oak Ridge National Laboratory
PHAST	Process Heating Assessment and Survey Tool
PSAT	Pumping System Assessment Tool
SEN	Save Energy Now program

Introduction

The industrial sector accounts for nearly 32% of the total energy demand of the U.S. (EIA 2018). As of Fall 2018, the U.S. Department of Energy's (DOE) Better Plants Program has helped save over 1 QBTU since the program began in 2011 (DOE 2018a). While 12% of the U.S. manufacturing sector's energy footprint is represented by Better Plants Partners, that leaves many opportunities within the sector (DOE 2018a). To help identify these savings, the DOE developed energy system-analysis software tools in the '90s and '00s (see Figure 1 and Table 1) allowing industrial facilities to quantify energy savings from potential projects (Leach, McElhaney, and Wright 2010). DOE energy experts utilized these tools in the 993 Energy Savings Assessments (ESAs) conducted as part of the Save Energy Now Program (SEN) where they identified nearly 170 TBTU per year savings. They are also currently used in the Better Plants In-Plant Trainings (InPLTs), where attendees are trained in their use. However, while energy savings opportunities, and thus the usefulness of these tools, have not changed much with time, many of these tools are no longer operable on modern operating systems.

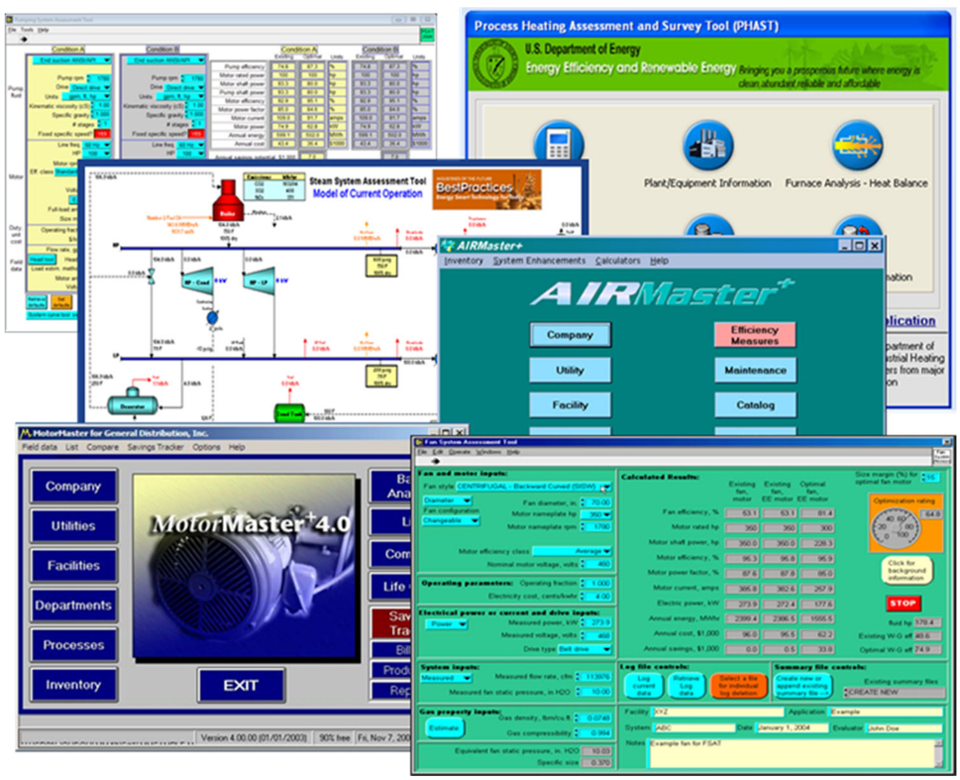

Figure 1. Screenshots of DOE Legacy Tools

Table 1. DOE legacy tools

System	Software tool	Last update	Currently supported?
Compressed air	AirMaster+	2012	Yes
Fans	Fan System Assessment Tool (FSAT)	2005	Yes
Motors	MotorMaster+ MotorMaster+ International	2007 2007	No No
Process heating	Process Heating Assessment and Survey Tool (PHAST) Process Heating Assessment and Survey Tool – Excel (PHASTEx)	2010 2016	Yes Yes
Pumps	Pumping System Assessment Tool (PSAT)	2008	Yes
Steam	Steam System Assessment Tool (SSAT) Steam System Modeling Tool (SSMT)	2008 2015	No Yes

This has sparked an initiative to revitalize these tools into a new, open source, combined software tool suite, MEASUR (Manufacturing Energy Assessment Software for Utility Reduction) (DOE 2018b). Designed for industrial energy coordinators, plant managers, engineers, utility programs and EM&V consultants, and any personnel who are interested in improving system efficiency and measuring potential savings opportunities, and built upon the original DOE software tools, MEASUR can assess and compare energy use within pump, fan, process heating, steam, motors, and compressed air systems (screenshot in Figure 2). There are over 40 equipment and property calculators for simple energy-related calculations and analyses.

MEASUR is available for Windows, Mac, and Linux, and is open source and open access, with the code bases and program available for free download and use. Being open source allows users to customize MEASUR to fit their processes or use the code as a starting point to developing real-time system analysis. It will also allow users to directly suggest code-base additions to update the tool for all users. Suggestions are then vetted by the MEASUR team before any suggestions are incorporated.

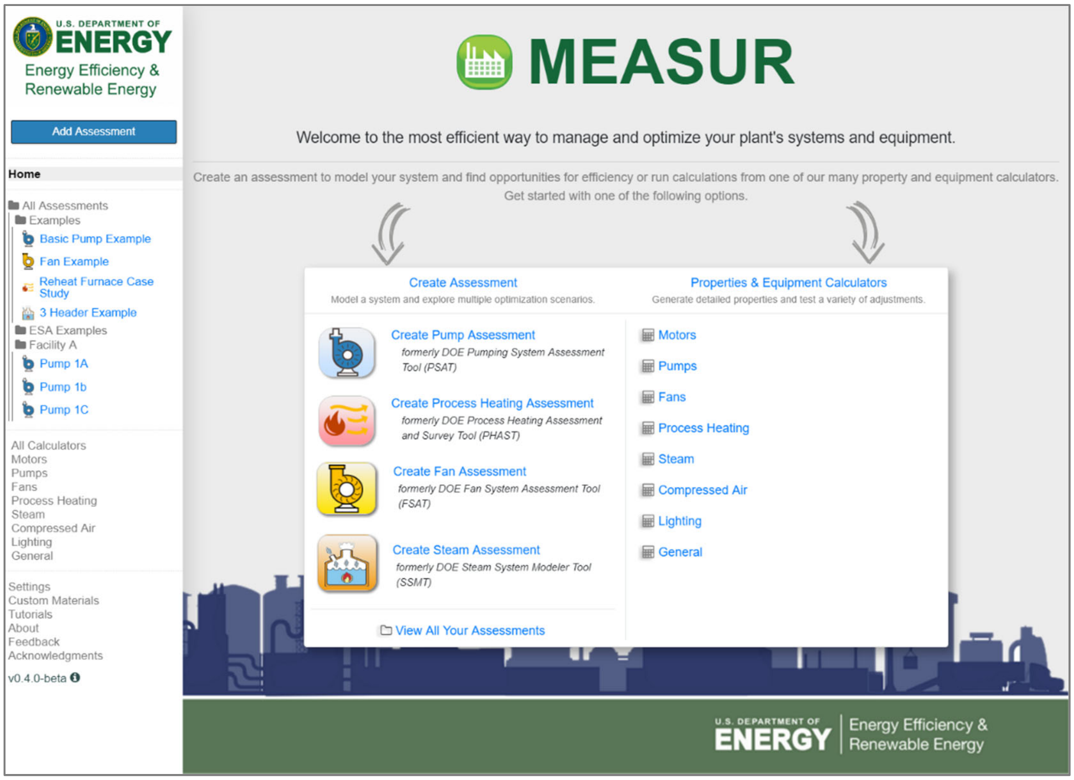

Figure 2. Screenshot of MEASUR home page

This paper hopes to begin establishing the validity of the MEASUR software by comparing it's results to that of the well-established legacy tools. Additionally, this paper will discuss MEASUR's usability improvements over the legacy tools and describe third-party development utilizing open-source framework for real-time sensor systems and efficiency optimization

Algorithm Verification

As the accuracy of any software is paramount, the MEASUR team has, from the beginning, done its best to insure and preserve its validity. While a full validation of MEASUR is in the planning stages, there have been many, less formal, checks to MEASUR's accuracy.

First, MEASUR's calculation algorithms are all based on previous incarnations of the tools, which were all based on physics, standards, engineering fundamentals, and well-established empirical correlations (Reed 1986; Moran and Shapiro 2000; ASME 2010a, 2010b, 2010c, 2010d; DOE and McCoy 2007; HI 2015; DOE 2003, 2004; IAPWS 2012; AMCA 2016). The legacy tools were developed in conjunction with equipment experts, trade associations (e.g., the Hydraulics Institute, the International Heating Equipment Association, and the Air Movement and Controls Association), and technical advisory committees (consisting of universities, equipment manufacturers, energy utilities, auditors, and energy resource centers) to insure accuracy from the beginning (Leach, McElhaney, and Wright 2010). They were also vetted after their releases; although no formal reports were produced, they were found to match closely with observed energy use and savings.

Additionally, a series of informal evaluations are being performed by DOE experts and stakeholders. These experts will include Better Plant's InPLT trainers and Industrial Assessment Center (IAC) directors who will utilize MEASUR within their training and assessments, and compare the results to those obtained by traditional calculation approaches. Finally, the developers have been speaking with various utilities and program implementers about testing the tool.

In addition to expert review, an indirect method was employed to verify MEASUR's validity: comparing the results of MEASUR to the results of the SEN ESAs. During the SEN Program, almost 1000 ESAs were completed between 2006 – 2011, providing almost 5500 recommendations to save nearly 170 TBTU/year energy savings. While not all the detailed assessment data was saved, the MEASUR team was able to obtain some copies of original input data and results from several ESAs. This data was entered in MEASUR to compare the results generated by MEASUR to the tools used during the assessments. Most estimated savings calculated by the legacy programs and MEASUR matched within several percent (see Table 2). Variations in the process heating assessment results are likely due to known improvements to the algorithms. For example, there were some major algorithm improvements relating to the calculations for opening losses: in the version of PHAST used in ESAs, there was no consideration given to the ratio of the dimensions of the opening (i.e., view factor) or surface emissivity, which were included in subsequent versions, including MEASUR. Additionally, legacy PHAST's wall losses calculation did not consider the effects of wind velocity, surface emissivity, or the orientation of the surface. The data needed to more accurately compare MEASUR with the reality of those facilities is not present in the reports of the ESAs, so were estimated based on likely conditions and the known assumed values in the code, as appropriate[1].

[1] To account for some MEASUR input fields not present in original data the following assumptions were made:

- Flue gas: Fuel Temperature = 65 °F;
- Wall: Wind speed = 0 mph, Surface Shape / Orientation = horizontal cylinders, Surface Emissivity = 0.9;
- Opening: Surface Emissivity = 0.9, set the number of openings such that the calculated area equaled the legacy tool's area user input;
- Charge Materials: Water Vapor Discharge Temperature is equal to Outlet Temperature, Water Content as Charged is the same as the legacy tool's net moisture user input, Water Content as Discharged = 0.

Table 2. Relative difference of ESA results generated by legacy tools vs. MEASUR

Pumps & fans	Relative difference
Pump efficiency	0.16%
Motor efficiency	0.01%
Annual energy	0.28%
Fan efficiency	0.91%
Motor efficiency	1.11%
Annual energy	0.48%

Process heating	Relative difference
Net energy	4.8%
Gross energy	5.8%
Charge material	1.6%
Fixture	1.4%
Wall	9.9%
Cooling	3.9%
Atmosphere	10.2%
Opening	24.5%
Available heat	3.0%

Steam	Relative difference
Power generation	0.83%
Boiler duty	0.79%
Makeup water flow	1.69%
Total operating costs	0.37%

Previous versions of PSAT and FSAT did not have direct comparisons of baseline and savings opportunities available, forcing users to compare different opportunities and calculating the new power consumption themselves, resulting in complicated analyses. Figures 3 and 4 illustrate the differences in how PSAT2008 and MEASUR handle a pump replacement. PSAT2008, the user had to estimate the expected energy use of the system with a new pump based on the motor and drive efficiency and pump specifications. In MEASUR, the user enters the expected pump efficiency at the approximate flow, from the manufacturer's pump curve, and estimates energy use for the user. This algorithm difference makes it difficult to validate MEASUR's capability at estimating savings for these scenarios. However, given the similarity of the calculation algorithms for the baseline and alternative conditions and the very low difference in the results for the baseline conditions, it is very likely that MEASUR is still reasonably accurate.

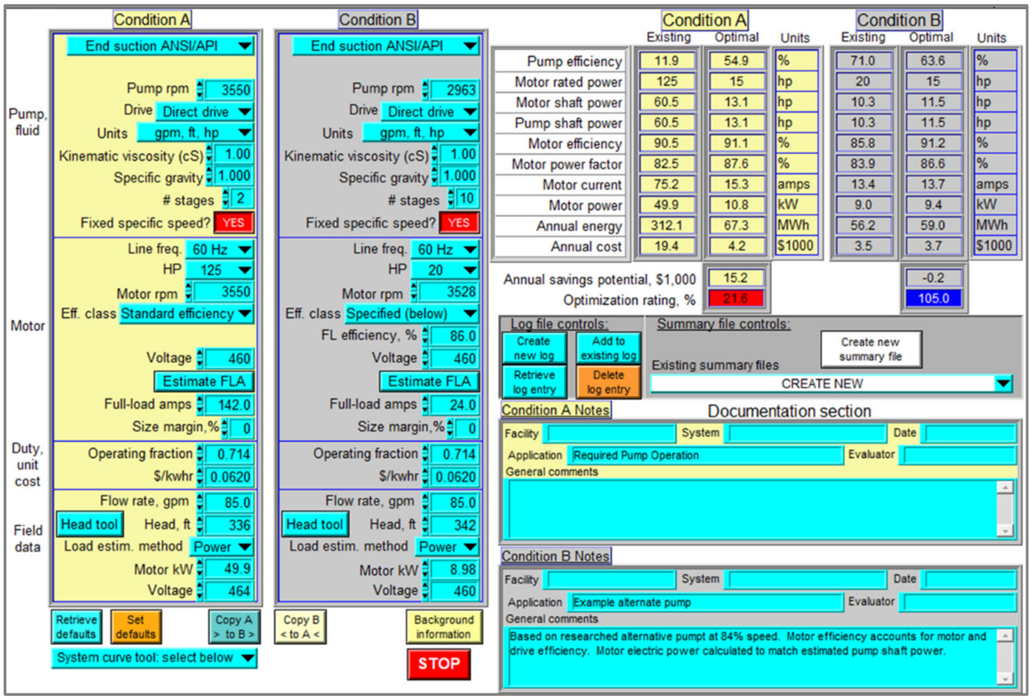

Figure 3. Screenshot of a pumping ESA's inputs and results in the legacy Pumping System Assessment Tool

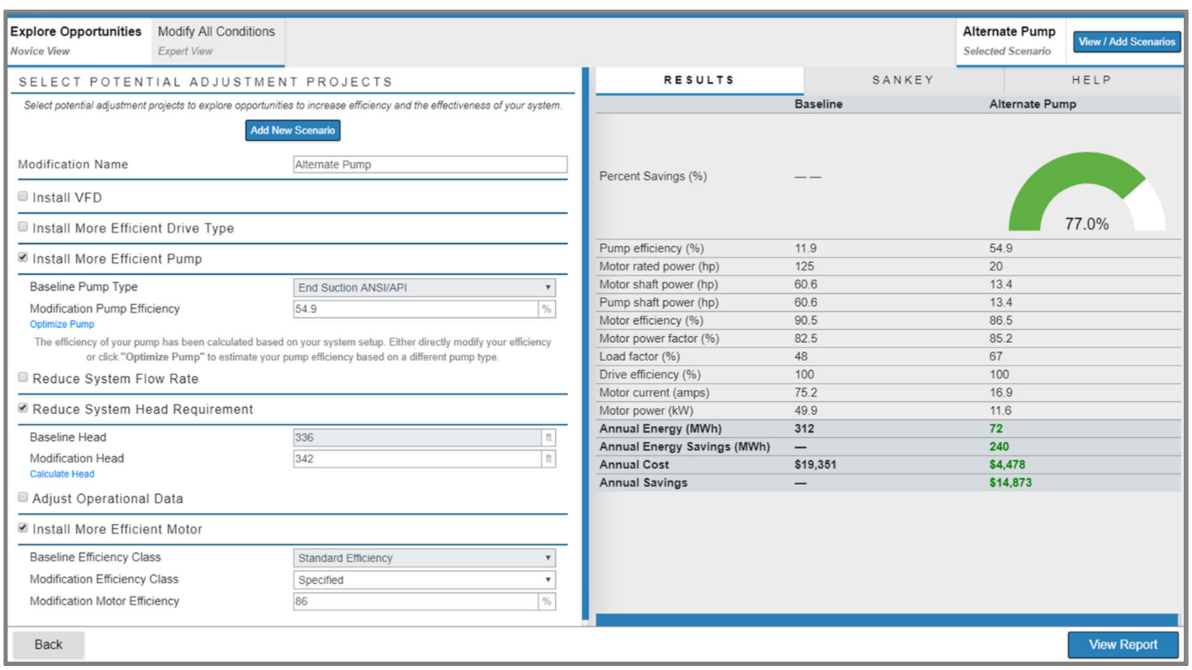

Figure 4. Screenshot of a pumping ESA's inputs and results reproduced in MEASUR

As there are no formal reports of the legacy tool's validity, follow-up surveys conducted at 6-months, 12-months and 24-months showed that the tool's results were reasonably close to the savings achieved after recommendation implementation. These surveys requested the status of the recommendation and facility personnel were asked to self-report an estimation for the energy cost savings related to the recommendation. These questions were used to calculate the achieved energy savings of the opportunity:

1. What is the current status of this opportunity (complete, in-progress, scheduled/planned, rejected, decommissioned)?
2. The original estimate of energy cost savings for this ESA savings opportunity was {$/year}. In your opinion, will you achieve less, the same, more or none of these annual cost savings?
    a. If less or more, what is your estimate of the difference, in percent?
3. Was this saving opportunity implemented elsewhere in your plant (yes or no)?
    a. If yes, please estimate additional cost savings from in-plant replication as a multiplier of the original savings.

Oak Ridge National laboratory (ORNL, the managing lab of SEN and Better Plants) was able to get feedback for 3700 recommendations at 6-months, though follow-up calls had fewer responses (1286 at the 12-month mark and 2338 at 24-months) (ORNL 2012). As Figure 5 shows, these follow-up calls show that 1103 recommendations were implemented, 604 were described as "in-progress" and a further 979 as "planned" (these values represent the status as of the final successful follow-up call).

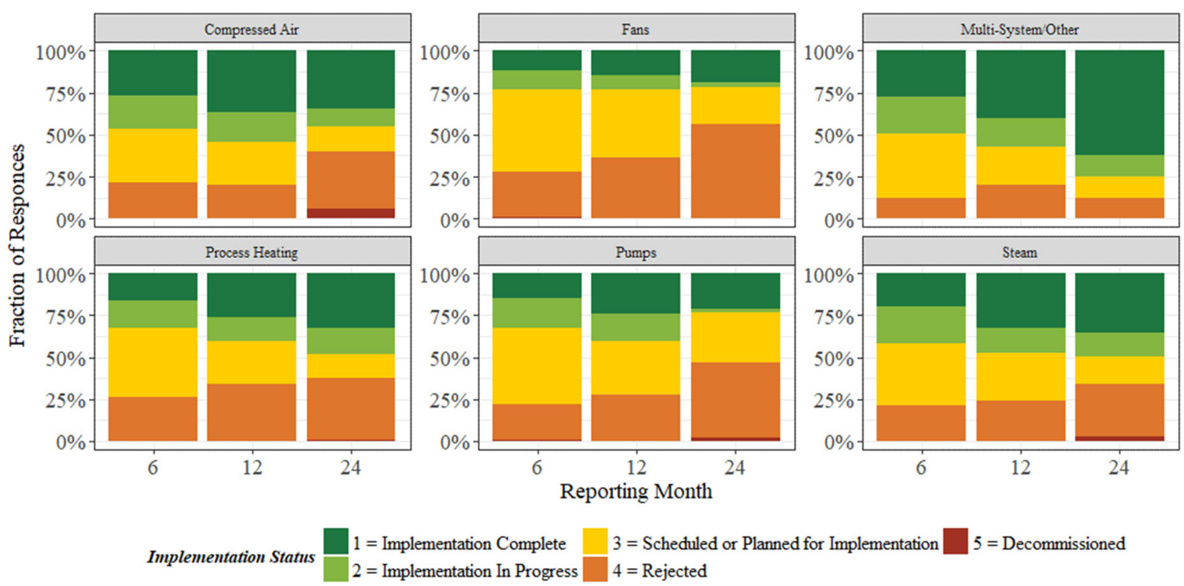

Figure 5. Recommendation status at 6, 12, and 24-month follow-up calls

Most of these savings were estimated using the legacy DOE software tools, making comparing estimated savings to actual savings a proxy for testing the validity of the legacy tools and MEASUR. For recommendations where the last reported status was "Implementation Completed", the ratio of actual savings to estimated savings (the fraction of estimated savings that was achieved) was calculated. Overall ESA types, on average, 115% of estimated savings were achieved (partially due to some recommendations being implemented multiple times within the same corporation), though this varied between type of ESA and the size of the facility.

$$Fraction\ of\ Savings\ Achieved = \frac{Actual\ Savings}{Estimated\ Savings} \quad (1)$$

Figure 6 illustrates the spread of the fraction of estimated savings achieved. Most (n = 853, 77%) of these recommendations were confirmed to be approximately what was estimated during the assessments. The first two bars all represent actual savings being less than the estimated (n = 156). The thin bar, centered around 1, represents all the recommendations where the achieved savings was reported to be the same as estimated. The last bars represent savings greater than expected (1-2) and savings from implementing the recommendation on additional equipment (2-2+). Table 3 shows the breakdown of the ESAs and their recommendations by facility size (based on primary energy use: small being less than 30 billion BTU/year, medium 30 – 500 billion BTU/year and large, greater than 500 billion BTU/year) and type of assessment. It also shows the average fraction of savings achieved for each breakdown and the range of Site Energy Consumption (in MMBTU) for each type of ESA.

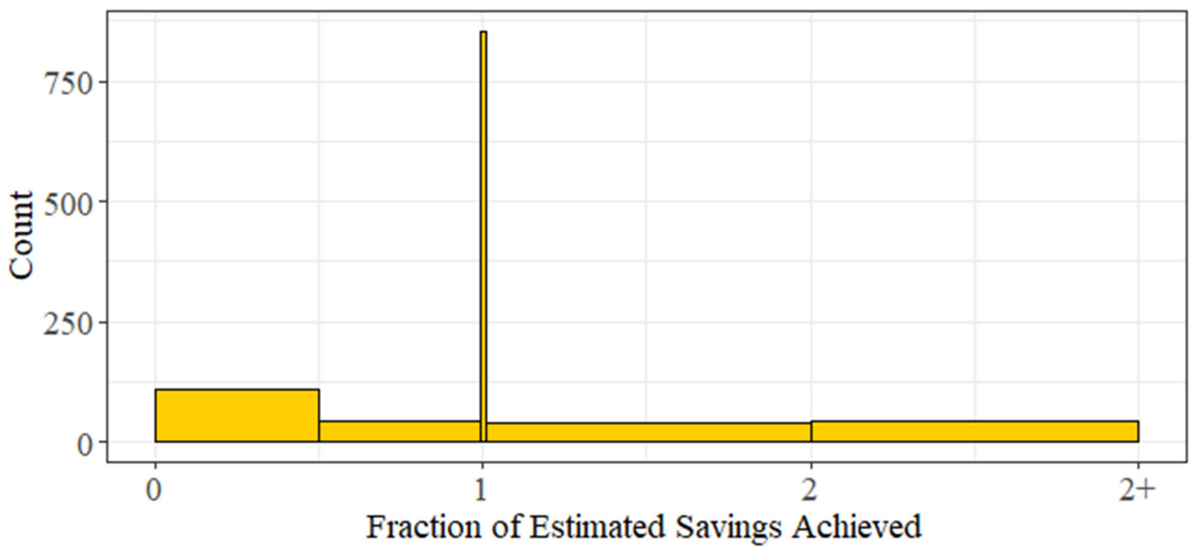

Figure 6. Histogram of the distribution of the fraction of estimated savings achieved

Table 3. Breakdown of ESAs by type and facility size

ESA type / facility size	Count			Average fraction of savings achieved	Site energy consumption (MMBTU)	
	Implemented	Recommendations	Assessments		Average	Range
Compressed air	159	669	145	127%	1,700,638	40,956 - 11,480,300
Fans	19	239	45	116%	5,809,176	255,411 - 15,574,477
Process heating	219	1162	226	104%	4,554,424	5,200 - 36,413,000
Pumps	58	375	86	95%	9,433,002	139,680 - 93,639,625
Steam	542	2220	341	120%	7,188,069	25,000 - 171,196,096
Other	106	833	150	89%	15,175,025	1 - 200,174,738
Large	944	4547	816	116%	7,301,497	184,302 - 200,174,738
Medium	149	867	160	101%	212,098	40,956 - 473,558
Small	10	84	17	68%	10,944	1 - 27,500
Total / average	1103	5498	993	114%	6,034,384	1 - 200,174,738

Despite the MEASUR team's confidence in the tool's output, outside input is always appreciated. As an open source software, the algorithms used in the code are publicly and easily accessible for consultation and comment on GitHub (DOE 2019a). Additionally, several algorithm documents are in development; these will be ORNL reports written to aid in user's understanding of the computation behind the results and provide the physics and empirical-based formulas used in the code. Finally, as MEASUR is still in development, many "unit tests" are embedded in the code to test the assessment results after any changes to the code base. If the code is changed in such a way that changes the results of one of the tests, the developer easily will be able to see the error and identify what corrections needs to be made.

Usability

While accuracy is the most important aspect of this type of software, even the perfect model is useless if users cannot figure out how to operate it. Feedback on usability has been solicited from industrial users and equipment experts in an informal sense, and while overall responses were positive, the team developed a more formal survey and included links within MEASUR (https://www.surveymonkey.com/r/DOE-AMO-TOOLS) (DOE 2019b).

A study on usefulness and usability of the legacy DOE software tools was conducted in 2006 (Schweitzer, Martin, and Schmoyer 2008). Participants were sent copies of the software tools by mail on CD and asked to participate in a survey about the tools. Using a 5-point Likert scale, where 5 was "Strongly Agree", users were provided with several statements on the tools. The key results were that the "Software was beneficial overall" received an average score of 3.9 and "Ease of navigation and data input" received a 3.8. While many found the tool useful, only about 18.1% - 29.8% participants reported taking the action that they modeled in the software.

MEASUR endeavors to build upon lessons learned from the legacy tools. The tools are all combined into a single software suite with common data files, to reduce the burden on users' computers. Usability (e.g., ease of navigation, data input, results presentation, unit conversion, system applicability, easily visible help text for each data entry field) has been a consideration throughout tool development. Figure 7 illustrates several key usability features:

- Help for a complex user input field is readily available;
- Immediate results, when possible;
- Clear navigation for within the assessment (next and back buttons, links to each other page of the assessment);
- Clear navigation to elsewhere in the tool: the dashboard (folder icon) or home screen (house icon);
- Relevant calculators one click away;
- Ability to add custom database entries (e.g., fuels, charge materials, lighting fixtures).

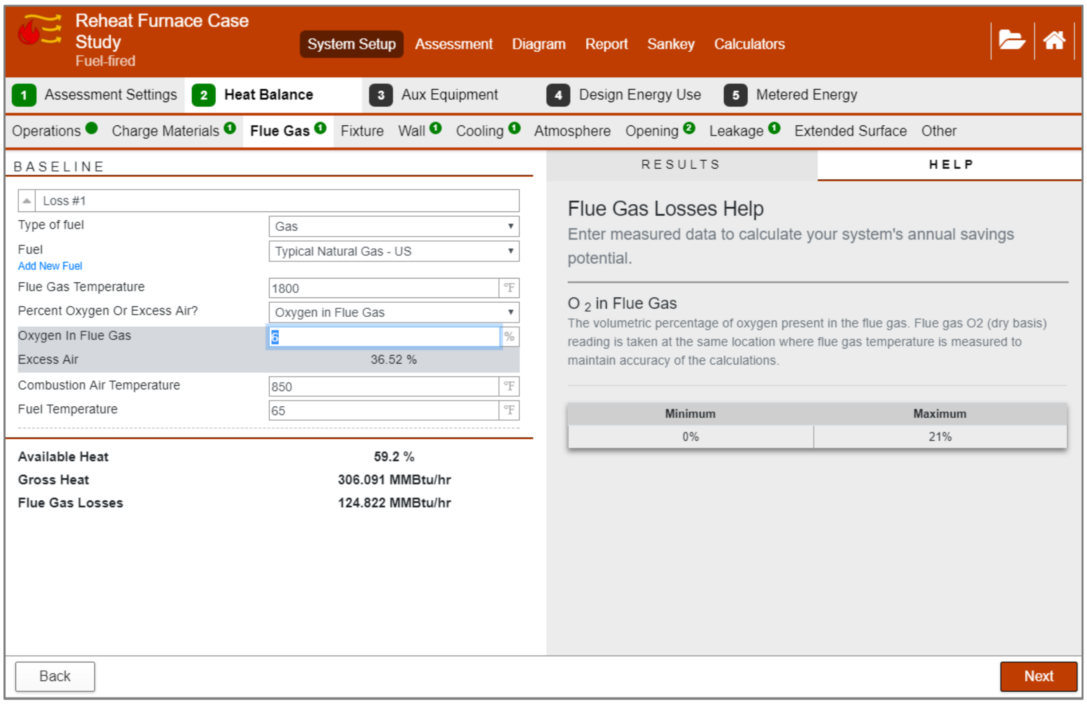

Figure 7. Screenshot of MEASUR highlighting usability features

Additionally, smaller calculators that were available in the legacy tools (often in obscure locations) are placed in a centralized location within MEASUR, easily accessible on the home page, and available via the Calculator Tab within each assessment. If the results would be used within the tool, they are also available next to the relevant user input. Table 4 lists all the calculators available in MEASUR as of v0.4.0, with more being added with each release.

Table 4. MEASUR Calculator List and Description

Motors	
NEMA Energy Efficiency	Shows the predicted efficiency of an induction motor, based on size, rotating speed and efficiency class
Motor Performance	Plots current, efficiency, power factor vs motor shaft load for a given motor description
Percent Load Estimation	Calculate percent load via slip method or field measurements
Motor Drive	Compares the annual energy cost of different motor drives
Replace Existing Motor	Estimates the energy and cost savings for replacing an existing motor with a higher efficiency motor
Replace vs Rewind	Compares the cost and energy of rewinding a failed motor versus replacing it with a new energy-efficient model

Pumps	
Head Tool	Calculate pump head using inlet and out pressures, elevation and pipe diameter
System Curve	Plot the system curve using static head and an operating point; can also plot pump curve
Specific Speed	Calculate the optimal specific speed for a pump and the penalty due to non-optimal operation
Pump Efficiency Curves	Estimate the achievable pump efficiency for various pump styles based on ANSI/HI 13-2000
Pump Curve	Develop a pump curve and explore the effects of changes in head, flow, pump speed and impeller diameter
Fans	
Fan Analysis	Calculate the power, flow rate, pressure and fan efficiency via pitot tube analysis
System Curve	Plot the system curve using static head and an operating point; can also plot fan curve
Fan Curve	Develop a fan curve and explore the effects of changes in pressure, flow, fan speed and impeller diameter
Achievable Efficiency	Estimate the achievable fan efficiency for various fan styles
Process Heating	
O2 Enrichment	Estimate fuel savings via adjusting the oxygen content of combustion and flue gases
Efficiency Improvement	Explore potential fuel savings from adjusting burner operating conditions
Energy Equivalency	Estimate required heat input when switching heat source from fuel-fired to electric or vice versa
Flow and Energy Used	Calculate the energy flow into the furnace by calculating the gas flow from data obtained by an orifice meter
Steam	
Steam Properties	Calculate the properties of steam, via IAPWS R7-97
Saturated Properties	Calculate the properties of saturated steam, via IAPWS R7-97
Stack Loss	Determine the amount of heat lost in the boiler stack gas
Heat Loss	Calculate the energy (heat) loss and outlet steam properties given inlet steam conditions and a % heat loss
Boiler	Determine the amount of fuel energy required to produce steam in boiler
Flash Tank	Determine the mass flows and properties of any resulting outlet gas and/or liquid for given inlet conditions
PRV W/ Desuperheating	Calculate the properties of steam after a pressure drop with optional desuperheating
Deaerator	Determine the required water and steam flows for a required feedwater mass flow
Header	Calculate the combined steam properties of multiple steam inlets
Steam Turbine	Calculate the energy generated or steam outlet conditions for a steam turbine
Compressed Air	
Leak Loss Estimator - Bag Method	Estimates the leakage losses in a compressed air system using the bag method
Pneumatic Air Requirement	Estimate the quantity of air required by a specific single acting or a double acting piston cylinder compressor
Receiver Tank Sizing	Calculate the required size of the receiver tank
Usable Air Capacity	Estimate the quantity of compressed air that is available for use
Pipe Sizing	Determine pipe diameter when the volumetric flow velocity, pressure, and design velocity are known
Velocity in the Piping	Estimate the velocity of compressed air throughout system piping
System Capacity	Determine total capacity of compressed air system or specific pipes and receiver tanks
Operation Cost Calculations	Estimate the cost of operation of the compressor in both fully and partially loaded instances
Lighting	
Lighting Replacement	Calculate the energy savings associated with lighting opportunities
General	

Pre-assessment / Screening	Compare the relative energy use of equipment to prioritize energy evaluations and opportunities
Unit Converter	Perform quick unit conversion calculations
Combined Heat and Power	Conduct a preliminary screening of the potential cost savings from CHP
Cash Flow Diagram	Plot the savings and costs associated with an investment
Power Factor Correction	Identify the capacitance (in kVAR) required for improving the power factor to the proposed level
CO2 Savings	Estimate carbon dioxide (CO2) emissions for given electricity and fuel uses

Being in active development, the team has pushed for participation in the ongoing feedback survey (located on Survey Monkey) that has been active since January 23, 2019. The team has solicited responses from AEE webinar attendees, IACs, utility program and EM&V consultants, and Better Plants Partners; additionally, a link to the survey was added to MEASUR. Survey questions are all optional and designed to establish the user's level of awareness with the previous tools, MEASUR's usability, and suggestions for further improvement. The survey asks for basic demographic information (contact information, business type, and the facility that was analyzed using MEASUR's annual cost of energy) and several questions about the respondent's use of MEASUR. There are also questions regarding the ease of use, the applicability of help text and warnings, and usefulness of the results (e.g., if they found any energy savings measures, if they think MEASUR will result in more actions taken). Several questions use a 5-point Likert scale with the high end indicating high usability, confusion, usefulness, or clarity, depending on the question. In addition, each Likert scale question had a corresponding free answer section for further comments. There were also two free answer questions regarding any comments/suggestions and overall impression.

Any collected results will be presented, including number of surveys taken, summary of the demographics, results of the Likert scale questions and quotes from the free answer sections. This survey will remain open throughout beta development to maximize the user input received.

3rd Party Development

In addition to the development by the MEASUR Team, DOE also encourages development of the tool from other areas. Over the 2018-2019 academic year, they sponsored a Computer Science Capstone project at Tennessee Technological University. Using the AMO Tools Suite (the C++ calculation engine of MEASUR) and taking inspiration from the MEASUR's user interface, several students have developed MIMIR, which is also available on the ORNL AMO GitHub page (DOE 2019a).

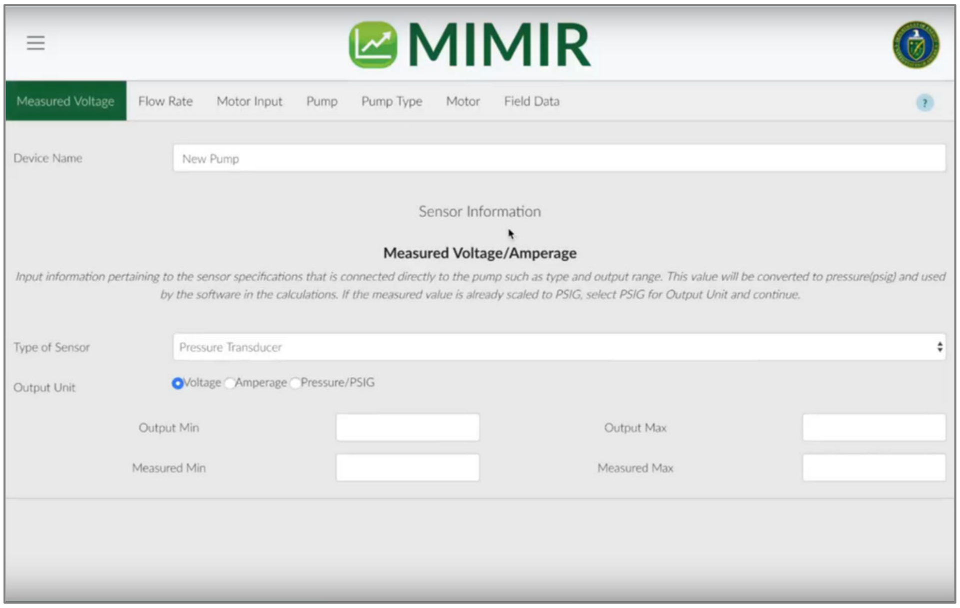

Figure 8. MIMIR sensor input setup

When completed, MIMIR will take real-time sensor data (e.g., flow rate, suction and discharge gauge pressure and elevation, see Figure 8) and run through the pumping system algorithms to compute and display pump and motor efficiency and energy use in real time, as shown in Figure 9 (Johnson et al. 2019).

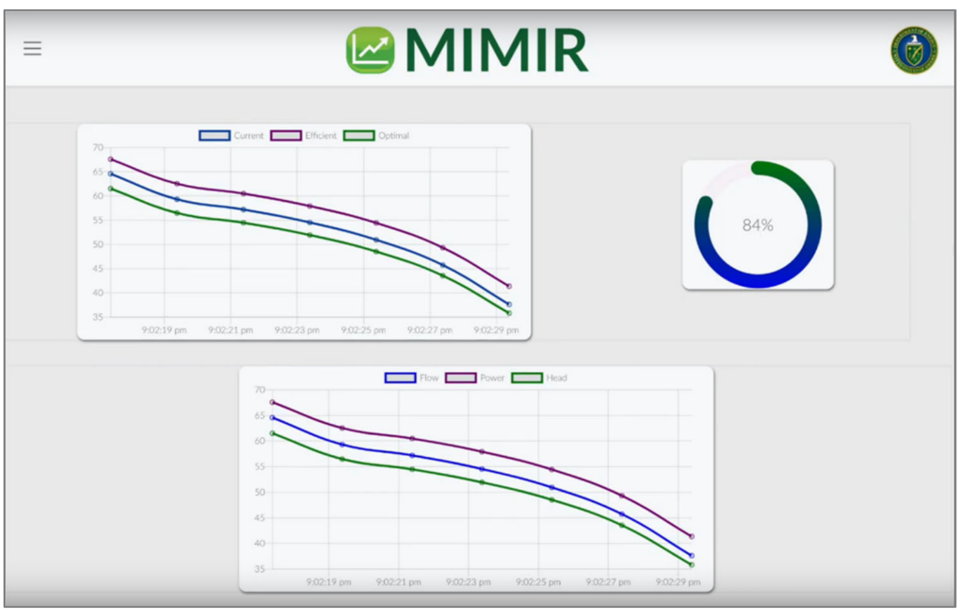

Figure 9. MIMIR results display

Conclusion

Previous incarnations of MEASUR's tools were used in SEN assessments for several years, providing manufacturing facilities with realistic, easy-to-obtain estimations of the energy impacts of energy reduction measures. The results from these tools was shown to be valid for energy savings estimations. MEASUR uses similar, but improved algorithms for its calculations that were shown to be nearly identical to those from PSAT, FSAT, and the SSAT, and close to PHAST (and the major differences likely caused by improvements to the algorithm). The survey results will hopefully confirm MEASUR's usability and usefulness for energy reduction analysis. It is also suitable for third-party development, as shown by the Tennessee Tech capstone project MIMIR.

MEASUR is still under development. Key features are still in the development or planning stages: a compressed air analysis tool and facility inventory databases (i.e., mimicking MotorMaster's custom inventory for all systems) are in development and other systems (e.g., Process Cooling or HVAC) are under discussion. Additionally, standalone calculators are slowly being added to the tool, as they are being suggested and developed. Feedback on new features (e.g., new assessment types and calculators) and feature improvement is being solicited from equipment experts, Industrial Assessment Centers, and utility program and EM&V consultants. There are also tentative plans to take the lessons learned from this project and the user interface style to develop an energy dashboard software for monthly energy and water consumption analysis.

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