Direct and Indirect Impacts of Robots on Future Electricity Load

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ABSTRACT

A confluence of global factors is fueling the utilization of robots across all segments of society. These include: rising human labor costs; commoditization of electronic components and computing power from ubiquitous device manufacturing and on-demand access to the "cloud", respectively; and the rise of machine-learning algorithms that enable robots to perform myriad tasks in diverse environments. In this paper, we ask the question:

How will the proliferation of robots in industry, businesses, and homes impact electricity load, both directly and through interactions with other end uses and devices?

Our work projects the future electricity load of societal 'robotification' as the framework for a thought-piece on the impacts of automation. Using industry sales forecasts and manufacturer data, we construct a stock-accounting model to project robot electricity consumption through 2025. We estimate it will increase to between 0.5-0.8% of total U.S. electricity demand in 2025. Additionally, we develop a qualitative framework to investigate how consumption might change due to interactive effects that include:

1. High efficiency equipment to power robots
2. Reduced lighting and heating load in fully automated, "lights out" factories
3. Improved robot efficiency through R&D
4. Robot replacement of tasks previously performed by humans
5. Increased productivity in industrial operations and ease-of-use in domestic applications

This paper seeks to begin a discussion on the load impact of ubiquitous automation and to motivate case studies to quantify the net load impacts of robots in specific instances across all sectors.

Introduction

A 2013 Oxford study by Frey and Osborne found that 47% of jobs occupied by humans are "highly susceptible" to automation (Frey et al. 2013). To put this into a historical context, technology advancements have been upending labor paradigms since the dawn of agriculture. The Industrial Revolution replaced skilled artisans with unskilled labor organized into discrete, repetitive tasks in assembly lines. Electrification in the late 19th Century allowed many stages of the production process to be automated, which in turn increased the demand for relatively skilled blue-collar workers to operate machinery and highly-trained white collar workers to manage teams of operators. Fast forward to the 21st Century and the continuation of this trend may disrupt nearly half of the modern labor force due to the advent of robotic automation and machine learning algorithms.

The McKinsey Global Institute estimates that robot prices have fallen 10% annually in recent years and are likely to decline at a more rapid pace over the next decade (Manyika et al.

2013). Declining costs, leaps in pattern recognition through machine learning, and rising human labor costs are likely to converge to transform modern labor practices and workforces.

Projecting the impact of this new fleet of robots on electricity load is of critical importance to the energy industry. Key parameters are number of units, electricity consumption per unit, interactive effects with other end uses, and growth rates of all these parameters in future years. Rates of change for all these parameters is highly uncertain; for example, there are current efforts to increase the energy efficiency of individual robots, like the Chalmers University of Technology work reporting that a 40% reduction in total robot energy consumption can be attained by optimizing the smoothness of robot motions without sacrificing productivity (Chalmers Univ. 2015). Our study aims to lay an initial foundation to consider the net impacts of robots on electricity load and utility forecasting.

Methods

Robot Reference Case – No Interactive Effects

The International Federation of Robotics (IFR) produces statistics on robot markets and sales forecasts for the robotics industry. They divide all robots into three categories: industrial, professional service, and domestic service. The IFR estimates that 248,000 industrial robots were sold globally in 2015, representing a 17% year-over-year (YoY) increase from 2013. They project 1.3 million industrial robots will enter the market between 2016 and 2018, a higher number than those sold in the entire period from 2008 through 2015 (IFR 2016). The IFR also estimates that 25,000 professional service robots and 4.6 million domestic service robots were sold in 2014, most of which were autonomous vacuum cleaners (iRobot 2016). They expect another 152,375 professional service robots and 34.9 million domestic service robots to be sold between 2015 and 2018, representing a 23% YoY increase over that period.

Starting with the IFR projection of unit sales through 2018, we developed three sales-growth scenarios for industrial robots through 2025: Low at 10%, Mid at 17% and High at 24%. For service robots, we chose three more sales-growth scenarios: Low at 15%, Mid at 23% and High at 30%. In both cases, the Mid growth rate is developed from IFR historical or forecast data, as mentioned above. We assume the allocation of sales by robot type and segment remain constant.

We paired IFR sales data and forecasts with annual estimates of per-robot energy consumption (instantaneous power draw multiplied by expected hours of operation) for each robot category to estimate annual energy usage through 2025. Average power draw for each robot type was estimated using manufacturer specification sheets for a representative unit robot when available. Otherwise, engineering assumptions were made. Robust estimates for industrial robot energy consumption for each segment of industry would require an in-depth survey of the distribution of robotic equipment operating in industrial facilities and was beyond the scope of this paper.

Assumptions for energy consumption are presented in Table 1. Change in the number of operational robots for any given year is calculated as the difference between projected unit sales and the yearly robot turnover, assuming an average lifetime for each robot type.

Table 1. Energy usage assumptions by robot type.

Robot Type	Instantaneous Power Draw (Watts)	Daily Operating / Charging Hours	Annual Energy Usage (kWh/Unit)	Lifetime (years)
Industrial				
Average Industrial	3,000	20	21,915	14
Professional Service				
Unmanned Aerial Vehicles (Military-Use)	3,000	5	5,479	2
Unmanned Ground Vehicles	5,000	4	6,392	2
Demining	1,100	1	452	2
Milking	540	6	1,085	8
Barn Cleaners / Robotic Fencers	540	5	986	8
Field Robots	540	5	986	8
Robot-Assisted Surgery	2,750	3	3,013	15
Other Medical	2,750	3	3,013	15
Automated Guided Vehicle	425	3	466	8
Mobile Platforms	19,700	3	21,586	8
Cleaning Robots	140	2	102	5
Rescue & Security	550	2	326	4
Inspection & Maintenance	810	2	592	4
Average Professional	4,096	2	2,805	8
Domestic Service				
Handicap Assistance Robots	275	7	703	5
Personal Assistants	150	7	384	5
Vacuum	35	2	26	5
Lawn Mowing	290	1	58	5
Other Cleaning	35	2	26	5
Education & Research	75	2	62	3
Robot Toys	30	2	25	3
Fully Autonomous EVs	1,950	6	4,273	8
Average Domestic	53	2	43	5

Figures for robot sales, operational robots and reference case robot load are given in Table 2 for the Mid case (17% industrial robot and 23% service robot YoY sales growth rates). The reference case represents only the plug load consumption of all operational robots and is not necessarily indicative of the net load impacts for each robot type.

Table 2. Reference case robot electricity load is driven by growth in the total number of operational robots and unit sales[1]

Robot Type	Unit Sales (2014)	Total Robots in Operation (2014)	2014 Robot Load (GWh)	2025 Robot Load (GWh)	YoY Growth
U.S Total	**1,642,498**	**3,530,291**	**5,334**	**22,822**	**13.2%**
Industrial Manufacturing	**25,350**	**203,637**	**5,058**	**15,954**	**10.4%**
Automotive	13,943	112,000	2,782	8,775	10.4%
Electronics	3,740	30,045	746	2,354	10.4%
Rubber/Plastics	1,309	10,516	261	824	10.4%
Pharmaceutical	187	1,502	37	118	10.4%
Food/Beverage	748	6,009	149	471	10.4%
Metallurgical	1,683	13,520	336	1,059	10.4%
Others	3,740	30,045	746	2,354	10.4%
Professional Service	**10,957**	**45,079**	**153**	**4,475**	**30.7%**
Unmanned Aerial Vehicles (UAVs)	4,721	9,442	72	941	23.3%
Unmanned Ground Vehicles	852	1,705	16	202	23.3%
Demining	183	366	0	4	23.3%
Milking	1,807	14,456	18	226	23.0%
Barn Cleaners/ Robotic Fencers	56	447	1	4	17.9%
Field Robots	1,988	15,907	19	114	16.3%
Robot-Assisted Surgery	341	1,023	5	195	33.7%
Other Medical	86	257	1	49	33.7%
Automated Guided Vehicle	461	738	0	50	43.2%
Mobile Platforms	461	738	21	2,684	44.1%
Domestic Service	**1,606,192**	**3,281,576**	**123**	**2,393**	**27.0%**
Handicap Assistance Robots	1,540	7,702	9	71	19.3%
Vacuum	1,024,642	1,280,802	35	1,037	30.8%
Lawn Mowing	63,261	316,303	28	230	19.1%
Other Cleaning	63,261	316,303	9	71	19.1%
Robot Toys	453,488	1,360,465	42	651	24.9%

[1] Only significant contributors to the reference case robot load are included in Table 2.

In the Mid growth rate scenario, our projection indicates that aggregate U.S. robot electrical energy load will rise to 22,822 GWh in 2025 from a robot fleet of 49 million robots. By way of comparison, this is roughly equivalent to the electricity load of all refrigerators in the northeastern United States in 2009 (EIA 2009). In 2025, the clear majority of robots are non-industrial (98%), while most of the load is industrial robots (77%).

Our conservative, Low growth case projects consumption of 19,987 GWh from 31 million robots in 2025, and we estimate 26,218 GWh of consumption in the High growth scenario from 77 million robots.

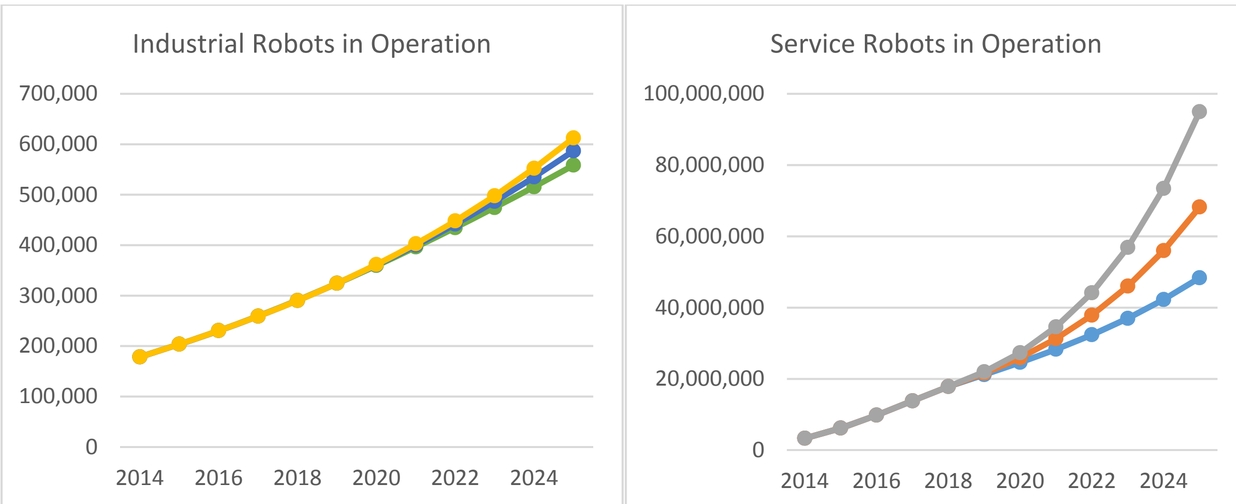

Figure 1. U.S. robot energy consumption by robot class – Low, Mid and High sales growth scenarios

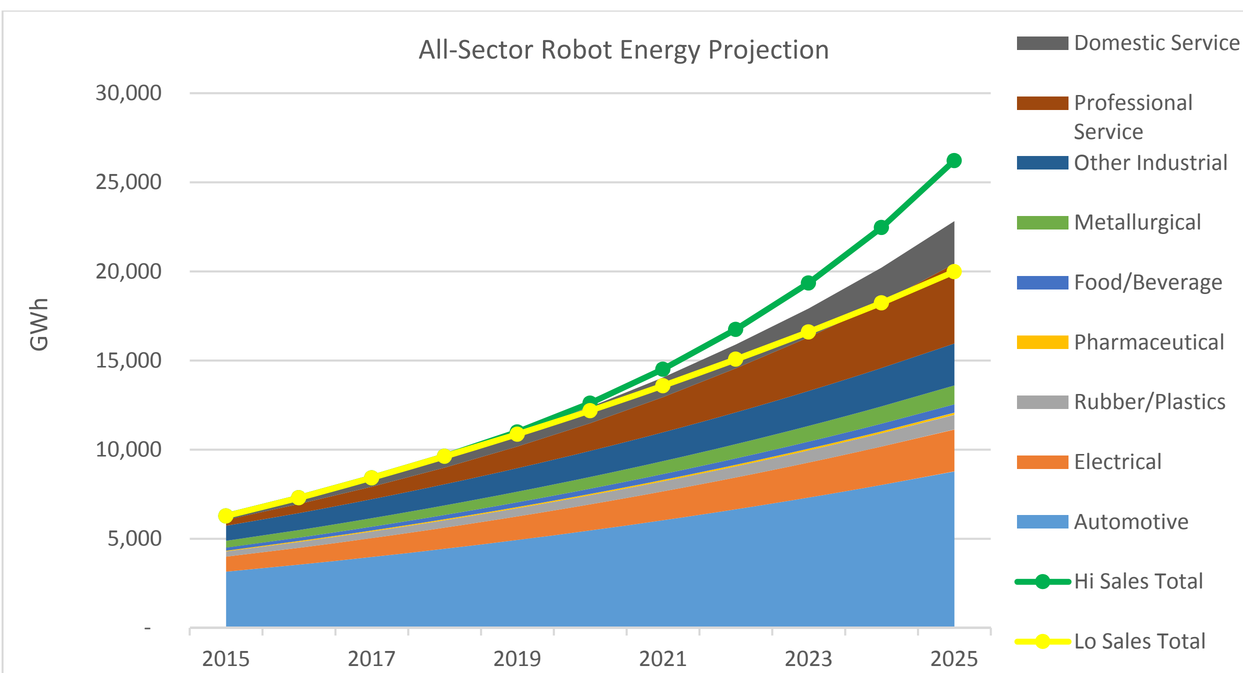

Figure 2. U.S. robot energy consumption by robot class – Mid sales growth scenario

Service robots maintain a dominant share of total operational robots over the forecast period, rising to 38.2 million robots in 2025 in the Mid sales growth scenario. However, their large numbers have little impact on the aggregate robot energy consumption forecast because they use relatively little energy on a per-unit basis. In fact, autonomous vacuum cleaners and robot toys make up 86.5% of total robot sales over the forecast period, but these units have an assumed consumption of around 30 kWh per year – an amount near that of a light bulb or laptop computer. Thus, they account for less than 5% of total reference case robot load over the forecast. Industrial and manufacturing robots are heavy users on a per-unit basis, consuming an average of over 21,000 kWh annually. Combined with a total unit count in the hundreds of thousands, they make up the lion's share of the robot load over the forecast period. Industrial robots account for 87% of the total reference case robot load in 2015, dropping to 77% in 2025 due to significant growth in service robot sales in the U.S.

Interactive Effects

The above robot load projections do not adequately reflect the net load impact of automation. Interactive effects must also be accounted for when traditional tasks are replaced or automated. For example, an industrial robot can replace a piece of equipment with identical energy consumption patterns and characteristics, resulting in no net load impact of automation. We have identified five interactive effects to capture the energy interactions between robots and the environments in which they operate; three that tend to decrease overall electricity consumption and two that tend to increase it.

Factors that decrease electricity consumption.

- <u>Factor #1</u> – Robots replace traditional machine tasks more efficiently
    - Robots replace automatable machinery and consume less energy than the retired equipment. The robot system could include highly efficient control systems as well as high efficiency motors and electronics, causing a net decrease in load. Another scenario could involve a single robot replacing multiple machines due to its relative dexterity and mobility, traits that could amplify as robotics research progresses.
- <u>Factor #2</u> – "Lights out"
    - Numerous operational changes to industrial and commercial facilities may occur with greater market penetration of robots. For example, there are already numerous "lights out" factories and warehouses, where industrial robots operate in unlit, unconditioned environments which allows facilities to eliminate considerable heating and lighting loads. "Lights out" facilities include a Philips factory in the Netherlands that manufactures razors with only nine quality assurance workers (Brooks et al. 2012) and the first-mover FANUC factory in Japan where robots have been building other robots since 2001 (Null et al. 2003).
- <u>Factor #3</u> – Robot R&D improves efficiency
    - Optimizing robot movement patterns can achieve a 40% reduction in usage, without sacrificing productivity, by eliminating jerky motions and acceleration (Chalmers Univ. 2015). Advanced lightweight materials will decrease all machine consumption in the coming decades and the most advanced systems (i.e., robotic systems) will benefit most from this trend.

Factors that increase electricity consumption.

- Factor #4 – Robots replace human-powered tasks and human-machine collaboration increases
    - Improvements in machine learning on large data networks will allow robots to replace an ever-increasing share of tasks currently performed by humans. Examples include autonomous vacuums, window cleaners, floor sweepers, delivery vehicles and forklifts. While the 2013 Oxford study indicates that 47% of jobs are automatable, the *net energy* impact of automating human tasks is uncertain. For example, automating such tasks as domestic cleaning and manual assembly of manufactured parts will increase net consumption. However, automation of clerking and technician-posts may replace humans which operated computers themselves, resulting in a negligible net change in consumption.
    - Human-robot teams are another major theme that could emerge in the future. Technologies such as virtual and augmented reality glasses, exoskeletons, and the like could mean incremental, additional power consumption. But they could also enable human-and-machine teams to complete more tasks faster, more powerfully, and more precisely.
- Factor #5 – Robots improve productivity
    - In the residential sector, a robot influx will increase machine assistance of handicapped individuals and embed human-machine interaction in everyday home and office life with personal assistants such as Pepper, the Japanese robot with emotional intelligence. The medical field will see a rise in surgical robots. Also, robot toys are likely to become increasingly energy-intensive as toymakers develop more product lines similar to Lego Mindstorms.
    - Automation of gas-powered machines, such as fully autonomous vehicles, will accelerate fuel-switching to electricity.
    - This effect can be particularly nuanced in the residential sector where the robot's utilization can be much greater than the machine it is replacing. For instance, a robotic vacuum may have a lower power draw than a plug-in vacuum, but the ability to schedule it daily may dramatically increase the frequency of vacuuming.

At this time, trying to quantify the net impact of these interactions on a facility or home's load would require developing a full set of assumptions that is beyond the scope of this paper and would rely upon comprehensive case studies which were not available in the literature. Our model is prepared to project robot load impacts on a sector-wide basis when proper case studies have been carried out to better quantify the five interactive factors. Nevertheless, we feel it is important to lay the groundwork for an exhaustive analysis of these interactions in the future.

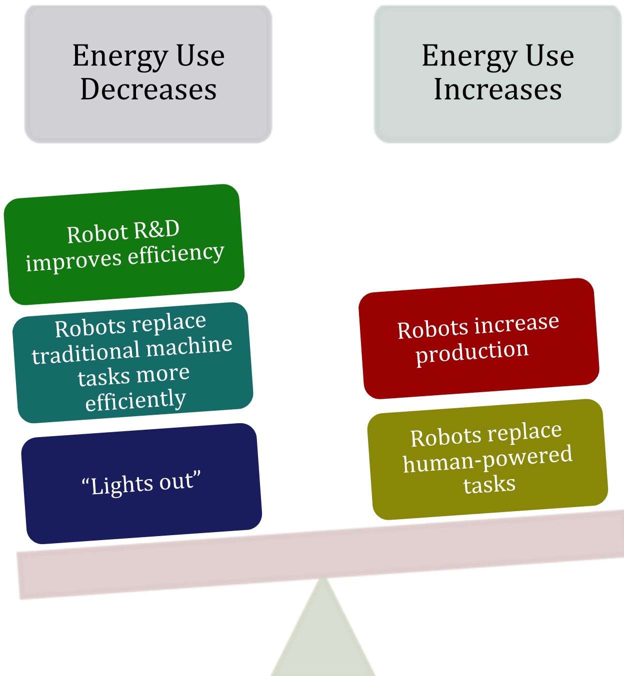

Figure 3. Depiction of interactive factors that will influence net load change due to robots. Efficient robot integration in all sectors will push the balance to the left.

Conclusions and Further Work

Further research is needed to develop case studies for specific instances of robotic automation in order to quantify the five interactive energy factors that we have described in this paper. Accurate measurement of these factors will allow for development of best practices that will maximize efficient robot integration into industrial facilities, offices and residential homes. In particular, service robots represent an imminent and unprecedented penetration of robots into our daily lives and may warrant significant attention from utilities. The opportunities to improve the efficiency of the coming robot expansion are numerous and could include:

1. Increased R&D into robot motion patterns
    a. Incentivize manufacturers to optimize on energy consumption in tandem with their existing goal of maximizing performance.
2. Upgrade equipment when implementing robots
    a. This will be a significant point of turnover in the timeline of any facility and may represent a great opportunity to upgrade any process equipment.
    b. Incentivize C&I and residential robot manufacturers to integrate efficient electronics and motors into their robotics.
3. Improve integration of robots with a focus on support load minimization
    a. Optimize spatial orientation of robot process lines relative to other human-guided operations.
    b. Modify scheduling to minimize human presence and maximize the "lights out" effect.

In conclusion, our reference case projects total robot consumption at 22,822 GWh or 0.57% of U.S. total load in 2025. The five energy interactions described in this paper may combine to swing the actual 2025 net total robot load drastically above or below this figure. We have proposed a framework to categorize and analyze the energy interactions of all robot types across all sectors. With sufficient case studies to accurately quantify the interactive energy factors, we can develop robust forecasts to better estimate the expected electricity impact of the coming robot boom.

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