# 1 Introduction

In recent years, the anthropogenic global warming and its disastrous effects on the Earth's climate system have increasingly characterized the socio-political discourse all over the world. With regard to a variety of irreversible consequences, such as an increasing number of weather extremes, a reduced biodiversity or a rising sea level, the international community attempts to mitigate global warming by effective environment and climate protection. In this context, the United Nations Framework Convention on Climate Change (UNFCCC) formulates an ultimate objective of limiting the increase in global average temperature to 1.5°C compared to pre-industrial levels [UNT15]. Since the predicted climate change can primarily be ascribed to the enhanced greenhouse effect, climate protection substantially focuses on the reduction of $CO_2$ emissions directly correlating with the human energy demand. A long-term prevention of a dangerous climate change thus requires the development of innovative technologies ensuring the sustainable utilization of available energy resources and the zero-emission organization of everyday life. In addition, numerous research initiatives concentrate on improving the energy efficiency of current technical systems and processes thereby motivating an intense climate policy and a cross-generational environmental awareness. Accordingly, actual strategies on climate protection typically range from restructuring the energy sector through the expansion of renewable energies to a zero-emission infrastructure based on electric mobility and public transport. Further promising approaches can be ascribed to the industrial sector representing the largest share of global energy consumption with 37.8% (240.1 quadrillion BTU) in 2020, see Figure 1.1 [EIA19]. Regarding the energy intensity of modern industries, international studies thus predict a savings potential of 25% primarily based on the introduction of innovative technologies [IPC14]. Alternative approaches focus on sustainable process design exemplarily promoting the recovery of energy surplus or the reduction of dissipative energy losses.

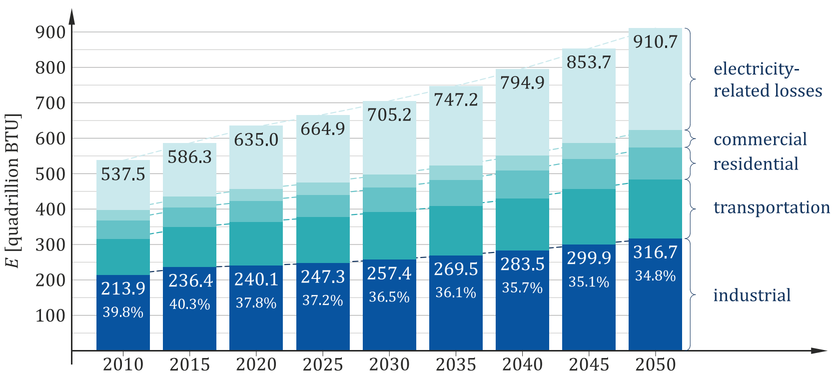


**Figure 1.1:** World energy demand by end-use sectors [EIA19]

Against this background, modern industries qualify for the establishment of sustainable production processes considering the economic, environmental and social needs of present as well as future generations. With regard to life cycle assessment, sustainability therefore reflects an enhanced notion of product quality addressing the cost-efficient but responsible use of natural resources. In consequence, a suitable conception of product design ensures climate protection within all phases of life, including development, manufacturing, logistics, usage and disposal. The comprehensive analysis of distinct product phases thus indicates a high potential for future reductions of greenhouse gas emissions ranging from ecological raw materials to the recycling of discarded products. In this context, product design and manufacturing industries provide a variety of innovative strategies in order to improve the sustainability and energy efficiency of required production processes. Accordingly, a first measure involves the revision or substitution of inefficient production facilities by innovative and ideally climate-friendly technologies. In addition, the immense industrial waste heat arising from energy-intensive industries is to be supplied to residential heating networks or transformed into electrical energy, respectively. Further benefits of sustainable production may include a long-term cost-efficiency, better working conditions as well as a better reputation of participating companies.

With regard to industrial large-scale production and high quantities, even minor process modifications may gradually have a significant energetic impact. In particular, the rising level of automation in manufacturing facilities and assembly lines provides a high potential for innovative and low-emission production technologies. In this context, repetitive processes meeting high requirements on precision and velocity increasingly involve industrial robots, whose energy efficiency is substantially affected by the underlying design and motion characteristics. Accordingly, global sales figures confirm a strong expansion of industrial robot applications over the past decade predicting further growth of the automation market, see Figure 1.2 [IFR19]. Due to large numbers of robotic manipulators within innovative production and assembly lines, energetic optimization of associated automation tasks may decisively contribute to the reduction of industrial emissions. Against this background, the potential energy savings of industrial robots range from upgraded hardware solutions to energy-efficient process and motion design.

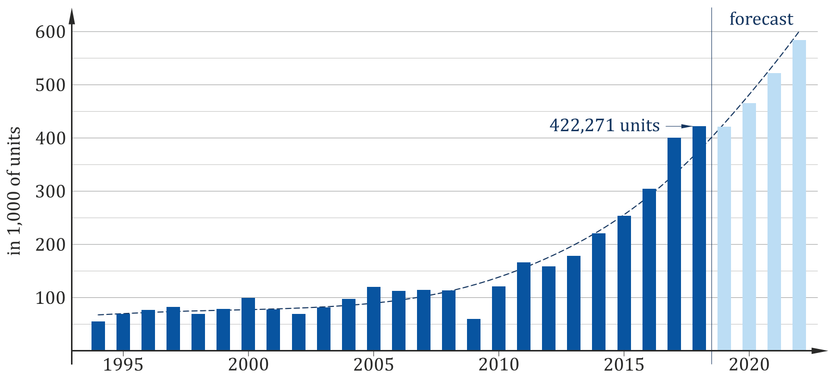


**Figure 1.2:** Worldwide annual supply of industrial robots [IFR19]

## 1.1 Research Approach and Challenges

The above-discussed concepts towards sustainable energy economics and industrial climate protection reveal a variety of opportunities and challenges for the energetic optimization of automation technology. In this context, the research approach presented here is devoted to the energy-optimal design of technical motions performed by automatic machines and industrial robots. Since the basic implementation of motion tasks typically neglects the associated energy expenditure, this thesis provides different concepts for the design and optimization of energy-efficient robot trajectories.

***Research Approach***

The energetic characterization and optimization of technical motions constitutes a promising concept for the reduction of energy demands and associated greenhouse gas emissions within manufacturing industries. Notwithstanding, today's industrial automation is primarily based on time-optimized motion design aiming for highest productivity and reduced production cycles. The resulting trajectories enable a highly dynamic operation of technical facilities, but tolerate an increased energy expenditure thus neglecting the ecological focus of future industries. In contrast, the field of mobile robotics provides a variety of solutions to cost-efficient path generation using discrete optimal planning, whose variations are considered state-of-the-art in robot locomotion. Since the accompanying workspace discretization rarely meets the extended kinematic and dynamic requirements of stationary robot applications, respective motion tasks typically concentrate on analytical trajectory planning as well as numerical optimization. In particular, the sophisticated kinematic and dynamic characterization of complex robot manipulators contradicts the presumed model simplifications of classical discrete planning.

Against this background, the present thesis proposes an extension of discrete optimal planning towards general motion tasks and arbitrarily complex robot systems. Given the conceptual design elements of discrete optimal planning, the developed methodology represents a combination of state space sampling and shortest path exploration. One central focus of this research approach thus involves the systematic modelling of spatial and temporal motion states as well as the subsequent evaluation of feasible state transitions. In this context, it is advisable to introduce a standardized state space definition reducing the set of admissible motion states to simplified state coordinates. On this assumption, the resulting configuration space enables the application of unified shortest path algorithms for individual robot systems and specific motion tasks. Having finalized the state space sampling, the set of feasible state transitions for each available configuration is evaluated by heuristic cost estimation.

A second focus of the proposed methodology addresses the systematic exploration of shortest motion paths within a directed set of discrete state transitions. With regard to efficient motion design, the considered exploration space may additionally reflect diverse concepts of energy recuperation or redistribution, whose negative cost estimates contradict the classical assumptions of metric state spaces within discrete optimal planning. In consequence, this thesis investigates specialized planning and exploration strategies providing the solution of shortest path problems in case of a generalized cost evaluation. Due to the discrete formulation of motion planning, the presented approach initially provides an approximation to energy-efficient