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Review

A Review of Exergy Based Optimization and Control

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Abstract: This work presents a critical review of the use of exergy based control and optimization for efficiency improvements in energy networks, with a background of exergy based analysis given for context. Over the past three decades, a number of studies using exergy were conducted to gain a performance advantage for high energy consumption systems and networks. Due to their complexity and the increased scale of the systems, the opportunity to misuse energy inevitability leads to inefficient operations. The studies accomplished in this area are grouped into either control or optimization to highlight each method's ability to minimize system irreversibilities that lead to exergy destruction. The exergy based optimization and control studies featured demonstrate substantial improvements (as high as 40%) over traditional methods based on the first law of thermodynamics. This paper reviews the work completed in the area of exergy based optimization and control as of the end of September 2019, outlines the progress made, and identifies specific areas where future work can advance this area of study. A relatively small amount of publications are available compared to other fields, with most work occurring in the area of exergy based multi-objective optimization.

Keywords: exergy; energy; optimization; control

1. Introduction

Energy efficiency and energy efficient system design are frequent topics among scientists, policy-makers, and consumers alike [1]. Improving the efficiency of energy consuming systems is ultimately cost effective and environmentally friendly, albeit usually not initially. For the past couple of decades due to increase in demand, consumption, depletion of natural resources, and the concern for the environment, efficiency and reduction of waste in energy systems has experienced a renewed emphasis. This increase in discussion led to recent improvements in smart technology (machine learning, Artificial Intelligence (AI), data science, etc.) and renewable energy (wind, solar, biomass, hydropower, geothermal, etc.). Similar to other industries, research and development of renewable energy systems and smart systems are mainly conducted using energy analysis during both the design phase and the employment phase to control and optimize the flow and distribution of energy [2].

The First Law of Thermodynamics (FLT) governs the amount of energy lost or produced in a process; energy cannot be created nor destroyed. However, this analysis alone fails to identify the quality of the dissipated energy and how much work potential is available. To assess both the quantity and the quality of the lost or gained energy, both the first and Second Laws of Thermodynamics (SLT) must be used in conjunction with each other to provide a more thorough understanding of the conversion inefficiencies, termed exergy [3]. Exergy is defined as the maximum theoretical work that a system can achieve when it comes into equilibrium with the environment or the dead state [3].

To date, exergy analysis is primarily used during the design process because it allows researchers to understand and source irreversibilities in a variety of different systems, hence influencing the design and future efficiency of the system [4]. Therefore, it allows the researchers to optimize their design to make a more efficient system. In the past decade, due to improvements in computing technology and better understanding of computing algorithms, exergy analysis has increasingly been employed to optimize systems in the industrial, commercial, residential, and transportation sectors [5]. As the demands in these sectors increase and energy flows between and within increasingly complex systems, which are interconnected, a universal or common measure of energy flow termed exergy provides beneficial analysis and control opportunities. Much like the mole in chemistry that serves as the "bridge" between atoms of different molecular weights and a universal measure for accountability, exergy provides the same capability in systems that consume and produce energy.

Thus, exergy based operation of systems has notable advantages over an energy based equivalent [3]. Since exergy:

- Provides a common "currency" that is compatible among varying units and dimensions within a system,
- Allows thermodynamic imperfections to be identified and therefore controlled and optimized,
- Accounts for work and heat separately, therefore allowing them to be controlled and optimized separately.

Current and future networked systems in housing, transportation, power, or the military will benefit from exergy analysis as engineers are better equipped to improve these systems by understanding the irreversibilities that degrade efficiency. Jain refers to energy networks of multiple components, flows, and time scales operating towards a goal as an Integrated Energy System (IES), and this work will use that nomenclature [6]. Future demands on energy resources, the need for mobility, and the ever present desire to keep efficiency high ensure that conducting analysis, optimization, and control in terms of exergy will have a place in the future. This work reviews the current efforts of other authors to use exergy combined with process control and optimization to improve efficiency in networks. A review of this narrow field, although potentially an avenue for substantial efficiency improvements, has not been completed. Admittedly, the subject is relatively new in the literature and under-populated with articles, but reviewing the literature now and compiling relevant works will give future researchers a comprehensive view of the current state and where further knowledge gaps exist. To the best of the author's knowledge, this work is novel, expected to fill a gap in the literature to date, and the compilation and review of these works will be of service to other researchers in the field. The search criteria to compile relevant literature contributions for this manuscript were exergy analysis, exergy optimization, and exergy control. These searches were conducted primarily through ScienceDirect, while Google Scholar and the library at the United States Military Academy served as a back-up to ensure all sources were gathered.

2. A Brief Utilization History of Exergy

The concept of "maximum useful work" was first conceived of by Gibbs in 1873 [7]. Although the concept was known and used for the following decades in engineering and science, the energy available to be used in a system was not formally labeled "exergy" until 1956 by Zoran Rant [8]. The effect of Rant's formal label was an acceleration of using the concept for "analysis" of a variety of systems in the remainder of the 20th Century and into the 21st Century. Historical events like the 1970s oil embargo or the recent droughts in the continental United States left engineers wanting for methods that would allow for a comparative advantage over previous work. The use of exergy is preferred in cases where a system is not in mutual stable equilibrium with its surroundings, providing the ability to isolate thermodynamic imperfections and identify the true available work [3]. Important works describing exergy further and demonstrating its place in the characterization of processes were written by Szargut, Brodyansky, and Kotas. Beginning in 1986, Szargut began writing about how to apply exergy concepts to industrial and environmental challenges, focusing on developing a framework for analysis of these systems [9–20]. His extensive contributions in this field continue to this day. In 1987, Szargut compiled his thoughts into a significant book that has served as an outstanding resource for researchers attempting to use the exergy concept [21]. Brodyansky's contributions to the field of exergy focus on the analysis and optimization of industrial processes. He recognized the potential efficiencies gained by analyzing and performing optimization in terms of useful work and began publishing studies on a variety of industrial processes beginning in the early 1990s [22–24]. His book, published by Brodyansky et al. in 1994, which provides detailed methods for conducting exergy based analysis and optimization in industrial processes, has proven to be one of the principal references in this area [25]. Kotas focused his work on exergy analysis to understand efficiency and losses in thermal plants. A series of two well-cited papers in the early 1980s led to an influential career attempting to increase efficiencies in the field [26,27]. His book, based on the findings in these key papers and originally published in 1985, was followed with two later editions and has been an important source of understanding for researchers evaluating the efficiency of thermal plants [28].

The United States consumes approximately 101 quadrillion (quad) British thermal units (Btu) or 2.55 gigatonnes of oil equivalent (Gtoe) per year of energy [29]. This energy spans every sector of our society (transportation, industrial, residential, etc.) and includes all forms of energy to include renewables, petroleum, nuclear, coal, and natural gas. Since only 11.5 quads, or 11% of the energy consumed in the U.S., is from renewable sources, any improvements in efficiency can help reduce the overall amount of energy consumed, especially the energy derived from fossil fuels. Because energy use scales in terms of quads, a relatively small percentage of improvement results in a considerable amount of reduction in energy consumed. Reducing the overall amount of energy consumed has the secondary effect of reducing carbon emissions. A number of previous works to improve the efficiency of energy systems focused on using exergy as the energy "currency" because it allows the locations, types, and true magnitudes of wastes and losses to be determined more readily [3]. A number of authors have used exergy to identify particular areas of inefficiency and recommend potential engineering improvements [30–34]. This method for analysis appears to be growing in popularity and provides detailed information on the thermodynamic imperfections of the system [3]. These imperfections, termed exergy destruction, wasted work, or wasted work potential, are the very inefficiencies that engineers spend their careers trying to avoid, minimize, or eliminate.

Exergy "analysis" refers to the use of exergy concepts to design a better, more efficient device or even an IES. Exergy is used primarily in the early phase of development to achieve better buildings, chemical processes, engines, etc. The National Aeronautics and Space Administration (NASA) even employs exergy analysis in the design of its rockets, space vehicles, and the International Space Station (ISS), to ensure every effort is made to increase efficiency and maximize useful work [35]. Based on their thorough review of exergy analysis in thermal power plants, Kaushik et al. concluded that the analysis alone in a number of studies was instrumental in better understanding performance and providing excellent efficiency improvement options [36]. Ozgener et al. noted similar findings in a review on exergy analysis of heat pumps, where energy analysis is more common, but exergy analysis provides engineers higher quality information in terms of inefficiencies, their locations, and magnitudes [37].

Both energy and exergy analyses were performed for gasoline and diesel based [38–40] automobile engines. Automobiles represent mobile energy networks, which fundamentally rely on the complex chemical, thermal, mechanical, and electrical interactions to operate. In addition to his aforementioned work with Brodyansky, Sorin et al. published a number of excellent manuscripts describing the analysis of chemical processes [41–45]. A number of outstanding contributions to exergy analysis of power plants, fuels, and renewables were conducted by Douvartzides et al., all of which provided a deeper understanding of these systems to aid in the struggle against climate change [46–49]. By understanding the complex multi-domain interactions, the mechanisms that lead to the irreversibilities may be identified and used to inform more sophisticated control algorithms.

Sarhaddi et al. preformed an exergetic analysis for a solar Photovoltaic (PV) array [50]. The energy and exergy efficiency of the PV array was derived by investigating the primary mechanisms by which energy/exergy was consumed as a function of the meteorological conditions. The efficiency terms were coupled with a gradient based optimization routine. The optimization routine identified PV design parameters that would minimize the destroyed exergy, improving the energy efficiency of the PV array. It was determined that the temperature difference had the greatest affect on exergy efficiency, and by reducing this difference, both the energy and exergy efficiency may be improved. This was an important finding, "since electricity and work are the same on an energy and exergy bases, the overall energy and exergy efficiencies for such devices (transformers, alternators, generators, motors and static converters) are the same. The losses differ greatly on an energy and exergy bases, as all energy losses are typically associated with waste heat. Most exergy losses are associated with internal consumption of exergy due to irreversibilities and little with waste thermal exergy emissions [51]".

Exergy based analysis of processes are highlighted here as an introduction to control and optimization and are only meant to be a representative sample of the distinguished works in the field. Due to the scope of this paper, the exergy analysis works outlined here are not comprehensive in volume.

3. Exergy Based Control and Optimization

Complex systems, or IESs, consisting of components like power plants, energy storage devices, and even autonomous vehicles, have multi-domain energy flows. Reducing energy consumption and waste to increase efficiency while maintaining the effectiveness of these networks is a challenge as they become more integrated, complex, and mobile or semi-mobile. The future is likely to bring advances to energy networks where a cluster of energy producers and consumers is providing a service as members of a stationary or potentially mobile network, while energy is transferred in a variety of forms and time scales. The current configuration of energy networks (micro-grids, grids, etc.) is static and isolated to one domain and time scale, but increasing complexity and necessity to increase efficiency will likely drive further integration of exergy analysis with control and optimization design in the future.

Employing an exergy based analysis to determine areas for efficiency improvement is a proven method and provides useful information at steady state. However, a relatively small number of cases over the past few decades showed an exergy derived dynamic model being used as the foundation for real-time optimization or control.

3.1. Exergy Based Model Predictive Control

Razmara et al. showed a 22% decrease in exergy destruction and a 36% decrease in energy consumption in an exergy based Model Predictive Control (MPC) algorithm managing climate control in a building [52,53]. Treating each room in the building of interest as a control volume and deriving an exergy balance for every *i*th room, exergy destruction occurring as a result of irreversibilities, flow, and heat transfer was captured accurately. Because this work designed and evaluated a rule based (on-off) controller, energy based MPC, and exergy based MPC simultaneously and clearly reported the results, the results made a compelling case that at least in the case of climate management in buildings, exergy based control was superior. Reddy et al. presented an exergetic MPC method to increase efficiency in buildings using a combination of Heating, Ventilation, and Air Conditioning (HVAC) and a micro-scale concentrated solar power system that reduced exergy destruction by 28% [54]. Because the building sector is responsible for approximately 40% of the energy consumed in the United States and Europe, Jonin et al. designed an MPC regulated Thermal Energy Storage System (TESS) to assist with reducing home energy consumption [55].

Baranski et al. conducted similar work using exergy based MPC to improve efficiency in buildings [56]. Using the works of Liu and Coffey in [57] and [58], respectively, as a guide, the work focused on improving the computational efficiency of the controller by decomposing known system exergy destruction models into sub-systems. Sub-system independent variables are then manipulated to minimize exergy destruction. Baranski et al. followed up by expanding the technique and applying the exergy based MPC algorithm for a building HVAC efficiency to a case study in [59]. A related comparison of energy versus exergy based control in buildings was conducted, demonstrating a reduction in building energy demand by 23.1% [60].

In 2018, Sangi and Müller sought to control advanced building energy systems [61]. Exergy was the "currency" of their work, and a hybrid controller combining agent based control with MPC was designed. The agent based control without MPC implemented allowed excess energy to be produced, leading to waste. When exergy was used to define the cost function, excess uncertainty and inaccuracy were introduced because the value of exergy at any moment depended on the corresponding magnitude of the ambient and system temperatures. Implementing an MPC layer minimized the uncertainty due to the model foundation of the controller and allowed for compensation of unknown or poorly understood interactions between components of the complex IES. Their work utilized a robust case study modeling a relatively complex IES controlling the climate in a building at the E.ON Energy Research Center (ERC) in Aachen, Germany.

A novel exergy based MPC to manage energy systems aboard ships was designed by Trinklein et al [62]. The thirst for more power to drive new devices that are increasingly dependent on energy and the reasonable expectation that propulsion and heating systems increase efficiency and reduce pollution are at odds with each other aboard naval ships. The growing desire to accomplish both goals simultaneously is accomplished by using an MPC that minimizes exergy destruction across all systems through a coordinated effort to minimize irreversibilities.

Control of a Vapor Compression System (VCS) was investigated by Jain and Alleyne, where they also employed an MPC to increase efficiency while demonstrating a superb capability to handle disturbances in real-time [63]. This work gained its accuracy from the detail and novelty of modeling the vapor-compression cycle. In particular, the model accounted for and gained its accuracy from rigorously modeling the most dynamic components of the cycle, the heat exchangers. The evaporator was modeled using two fluid regions and the condenser utilizing three, to account for the destruction of exergy due to changes in the temperature and enthalpy of each fluid regime in each component. Both energy based and exergy based controllers were designed and implemented; a 41.4% improvement in exergetic efficiency was realized, meaning that an exergy based MPC design was 41.4% better at efficiently using work potential than an energy based MPC design. The reason for the increased performance in an exergy based MPC scheme was that this method minimized irreversibilities in the system such as friction in fluid flow or heat transfer across finite temperature differences.

Working to improve efficiency in the gas industry, Salahshoor and Asheri demonstrated the utility of implementing exergy based MPC on Multi-Input, Multi-Output (MIMO) processes [64]. Hadian et al., which included Salahshoor, used an exergy-event based MPC approach to minimizing exergy destruction in IESs in a related paper [65]. The rate of exergy reduction, the rate of irreversibility, and the exergy efficiency were captured using the aforementioned exergy destruction balance methodology. The MPC was supplemented by including a closed loop Event Based Mechanism (EBM) with associated constraints to ensure control was applied as performance criteria were met. This work detailed the influence of the input and output weighting matrices, **R** and **Q**, on the stability, controller performance, and energy consumption of the plant.

3.2. Exergy Based Optimal Control

The work of Ray et al. minimized exergy destruction in a boiler superheater utilizing a Linear Quadratic Regulator (LQR) approach [66]. To ensure the longevity and safety of the boiler plant, steam temperatures were managed closely using a process of attemperation or the introduction of additional water stream after steam was made to reduce the temperature as needed. The optimal control scheme in this work minimized the exergy of destruction as disturbances like variations in fuel composition and flow were introduced. A robust analysis of the affects on exergy destruction of varying the quadratic **Q** and regulator **R** matrices of the LQR was included.

A novel optimal control method based on Hamiltonian principles was designed by Trinklein et al., for thermal management and optimization of electrical microgrids aboard an aircraft [67]. With an increased effort by the military and civilian sectors to exploit electrification of aircraft, managing thermal energy and maintaining the adequate effectiveness of the system to support on-board mission equipment requires rigorous control. The proposed Hamiltonian optimal control algorithm managed heat while ensuring adequate power generation and distribution to the necessary components.

3.3. Exergy Based Optimization

Farahat et al. contributed a valuable collection of papers in the area of exergetic optimization of a variety of solar energy gathering systems [68–72]. Much like other sources, this valuable and virtually endless supply of renewable energy is more effective at replacing fossil fuels on the grid and decreasing carbon emissions when its generation, storage, and distribution are rigorously optimized and controlled. Led by Naserian, Farahat and Sarhaddi also provided an exergy based tool for optimization of regenerative Brayton cycles, potentially further contributing to the efficiency improvement of energy production and reduction of carbon emissions [73]. In 2018, Ashouri et al. demonstrated exergetic optimization of a double pressure Rankine cycle coupled with a solar collector [74]. In the same year, Behzadi et al. wrote a comprehensive demonstration of the benefits of multi-objective optimization in a complex IES [75]. This work further expanded efforts to use exergy to improve the efficiency of renewable energy.

Ahmadi et al. optimized a transcritical carbon dioxide power cycle driven by geothermal energy and an irreversible Carnot refrigerator, providing yet another recent and relevant example of exergy as the currency in optimizing power systems that are the latest technology [76,77]. Capitalizing on the recent expansion in research and development at the nano scale, Ahmadi also led a team that demonstrated exergetic multi-objective optimization on a Braysson cycle [78]. A Combined Cooling, Heating, and Power (CCHP) plant, becoming more popular as an efficient alternative in dense residential areas, was optimized using multiple criteria by another group led by Boyaghchi [79]. Boyaghchi et al. also wrote a similar work utilizing the Kalina power cycle on trough solar collectors [80]. Ahmadi and Dincer also contributed to this area of interest, optimizing the cogeneration of a CCHP using exergy principles [81]. An important work on the multi-objective optimization of gas turbine power plants, written by Ahmadi and Dincer, was published in 2011 and has made great contributions to increasing the efficiency of one of the world's most widely used tools for power production [82]. In the same year, Barzeger collaborated with Ahmadi and others on the same topic [83]. Shamoushaki et al. built on this work by cleverly applying the multi-objective optimization algorithm used in other power system studies to improve the efficiency in a case study of the Aliabad Katoul power plant [84].

As an increasing percentage of renewables are introduced to the grid, researchers within the United Kingdom recognized the potential of exergy based optimization to cut peak demand while reducing the variability of apparent demand arising from embedded renewable generation [85]. The authors designed an optimization algorithm that minimized exergy loss in the grid based on demand information and balanced the supply and demand. Minimizing exergy loss is a better alternative to minimizing energy consumption because exergy is the potential to do useful work and exergy efficiency describes specifically how well exergy is extracted from a system. In the situation where a potential variety of fuel sources is available to provide service to the end user, an objective function minimizing exergy loss would choose the energy source best suited, which would not likely agree with a choice made based on energy efficiency.

In addition to other notable contributions to exergy understanding to include his aforementioned summary paper in [3], Dincer collaborated with Ahmadi and Rosen in 2011, 2012, and 2013 to publish four important exergy based optimization papers that provide insights into improving the efficiencies of stationary IESs used for heating and power [86–89]. The merits of these works are that they are general enough in their description of a poly-generation systems while still providing a useful framework for other researchers to utilize. Kilkis and Kilkis further noted exergetic optimization in poly-generation systems, offering a method to increase efficiency in a heat pump coupled system [90].

P. Ahmadi and Dincer also contributed at nearly the same time, in conjunction with Hajabdollahi, two manuscripts demonstrating rigorous exergetic optimization of processes that are relevant to efficiency improvement efforts in industry and power production [91,92]. These manuscripts provide excellent examples of multi-objective optimization in a shell-and-tube heat exchanger and a heat recovery steam generator as part of a combined cycle power plant. In similar work, Mozafari optimized the operation of micro gas turbines for reduced pollution [93]. This work was unique because it included the social cost of air pollution in the objective function, thereby reducing it as exergy was minimized.

Razmara et al. developed an optimal exergy based solution for an Internal Combustion Engine (ICE) [94]. ICEs are the primary power generation device used to propel traditional civilian or military based ground and air vehicles. By altering the control logic, the engines' inefficiency may be reduced. Using exergy principles, the primary mechanisms/conditions that affect the engine efficiency were identified and used to inform the combustion phasing controller, maximizing the SLT efficiency. The design of the ICE created a number of areas where temperature differences existed, creating irreversibilities. Irreversibilities within the system led to exergy destruction or loss of work potential. The SLT based controller minimized exergy destruction or indirectly system irreversibilities and therefore minimized the regimes where large temperature differences existed. The SLT based controller was compared to a more traditional FLT based controller, and the results indicated that an average of 6.7% fuel savings and 8.3% exergy savings could be archived using the SLT controller over the FLT controller.

4. Discussion

The body of work where exergy is used in conjunction with efforts to perform optimization and control in energy systems is relatively small. The majority of publications in this area describe variations of exergy based optimization. Table 1 shows the authors and their works featured in this effort. The compilation is an attempt to serve other researchers in terms of what research has been accomplished, a clear list of references, and what gaps potentially remain in the field.

Table 1. Summary of works related to exergy based optimization and control.

Author	Method	Investigated System	Implementation	Reference
Razmara et al.	MPC	Buildings HVAC	Design	[52,53]
Reddy et al.	MPC	Buildings HVAC	Design	[54]
Jonin et al.	MPC	Buildings TESS	Analysis and Design	[55]
Baranski et al.	MPC	Buildings HVAC	Design	[56,59]
Sayadi et al.	MPC	Buildings HVAC	Analysis and Design	[60]
Sangi and Müller	MPC	Buildings HVAC	Design	[61]
Trinklein et al.	MPC	Ship Energy Systems	Design	[62]
Jain and Alleyne	MPC	VCS	Design	[63]
Salahshoor and Asheri	MPC	Compressor	Analysis and Design	[64]
Hadian et al.	MPC	Industrial Processes	Design	[65]
Ray et al.	Optimal Control	Boiler	Design	[66]
Trinklein et al.	Optimal Control	Aircraft Energy Systems	Design	[67]
Farahat et al.	Optimization	Solar Collectors	Design	[68]
Ajam et al.	Optimization	Solar Air Heaters	Design	[69]
Sobhnamayan et al.	Optimization	PV with Water Collector	Design	[70]
Sarhaddi et al.	Optimization	PV with Air Collector	Design	[71]
Sarhaddi et al.	Optimization	Solar Parabolic Cookers	Design	[72]
Naserian et al.	Optimization	Brayton Cycles	Analysis and Design	[73]
Ashouri et al.	Optimization	Rankine Cycle	Analysis and Design	[74]
Behzadi et al.	Optimization	Solar Energy Systems	Analysis and Design	[75]
M.H. Ahmadi et al.	Optimization	CO_2 Power Cycle	Analysis and Design	[76]
M.H. Ahmadi et al.	Optimization	Carnot Refrigerator	Analysis and Design	[77]
M.H. Ahmadi et al.	Optimization	Braysson Cycle	Analysis and Design	[78]

Table 1. *Cont.*

Author	Method	Investigated System	Implementation	Reference
Boyaghchi et al.	Optimization	CCHP	Design	[79]
Boyaghchi et al.	Optimization	Kalina Cycle	Design	[80]
P. Ahmadi and Dincer	Optimization	CCHP	Analysis and Design	[81]
P. Ahmadi and Dincer	Optimization	Gas Turbine Plants	Design and Hardware	[82]
Barzeger et al.	Optimization	Gas Turbine Plants	Hardware	[83]
Shamoushaki et al.	Optimization	Gas Turbine Plants	Hardware	[84]
Boait et al.	Optimization	Renewable Energy Systems	Analysis and Design	[85]
P. Ahmadi et al.	Optimization	Heating and Power Cycles	Design	[86–89]
Kilkis et al.	Optimization	Poly-Generation Systems	Design	[90]
Hajabdollahi et al.	Optimization	Power/Industry	Design	[91,92]
Mozafari et al.	Optimization	Micro Gas Turbines	Design	[93]
Razmar et al.	Optimization	ICE	Analysis and Design	[94]

The works that highlight exergy based optimization are performed on a wide variety of processes. Most of the authors in this area focused on leveraging the benefits of exergetic optimization, outlined in the Introduction, to improve existing processes [73,75–89,91,92]. For instance, the work by a number of authors to improve the efficiency of gas turbine power plants is timely in light of the growth of installed gas turbine power plants over the past ten years [95]. Coal-fired power plants, on the decline over the past ten years, are being replaced by gas-fired turbine plants at a rate of 15% new installations over the same period of time. Record low natural gas prices leading to supply surpluses will drive this trend into the future, so the work by these authors to continue the efficiency improvements of these vital assets is important.

In addition to the optimization of power plants, other authors used multi-objective optimization to minimize exergy destruction in a number of power cycles (Brayton, Kalina, etc.), heating and power processes, or related unit operations [73,76–84,86–93]. It is no coincidence that there are multiple works dedicated to turbines, power cycles, and related processes. These processes are characterized by large temperature gradients, creating opportunities for system irreversibilities that are the source of exergy destruction. Because these processes are vital to the economy, the military, and typically contribute to an overall improved lifestyle within the population, it is unlikely they will not play a large role in society for the foreseeable future. Due to the scale and application to almost every sector of daily life, improving their efficiency using the exergetic optimization techniques described above even by a relatively small amount will have an exponential effect on overall energy consumption and the related environmental side effects.

The integration of renewables into the grid has increased by 11% over the past ten years and is predicted to continue in the coming years [96]. An impressive amount of work has been accomplished to optimize renewable energy systems and their integration into the electricity grid in terms of exergy [68–72,75,85]. The forecasted increase in renewable integration into the grid ensures that there are vast opportunities for future research in this area.

Of the manuscripts described above and outlined in Table 1 where exergy is used as the "currency" within the framework of MPC, all showed substantial efficiency improvements in building climate control, the gas industry, and in a vapor compression cycle [52,53,56,61,63–65]. As can be seen in Table 1, many researchers have addressed the design and analysis of control methods for building HVAC systems. As a result, more detailed information regarding the repeated research attempts are provided in an attempt to better understand the major differences between these particular studies. Studies with dissimilarly investigated systems will not be described in as much detail as system architecture and control based polices vary greatly based on the investigated system.

Razmara et al. postulated an MPC based control strategy to optimize the performance of a building HVAC system [52,53]. The energy network considered multiple ground source heat pumps applied to a three-story building. Multiple thermal zones were defined and controlled separately. The individual heat pump loops also included a compressor, expansion valve, and two heat-exchanger coils to which an evaporator and condenser were attached. The study compared a Rule Based Controller (RBC), an Energy based MPC (EMPC), and an Exergy based MPC (XMPC). The EMPC yielded a 18% and 24% reduction in exergy destruction and energy consumption when compared to the RBC, while the XMPC yielded a 22% and 36% reduction in exergy destruction and energy consumption when compared to the RBC. Source irreversibilities were reduced using the XMPC, leading to the aforementioned benefits.

Using the energy network as defined in Razmara et al. [52,53], Reddy et al. developed an optimal exergy wise predictive control for the combined Micro-Scale Concentrated Solar Power and HVAC system [54]. Unlike the previous study however, this study also included thermal energy storage, a micro scale concentrated solar power system, and an organic Rankine cycle. The energy network was simulated and controlled using EMPC, XMPC, and RBC based control strategies. A Monte Carlo simulation was also preformed to investigate the probabilistic analysis, which accounted for prediction uncertainties within the MPC. The EMPC reduced exergy destruction by 25.7%, leading to a 21.6% energy savings when compared to the RBC. The XMPC reduced exergy destruction by 28%, leading to a 23.2% energy saving when compared to the RBC. The Monte Carlo results indicated that there was a 50% likelihood of reducing energy consumption and exergy destruction by 23.5% and 27.5%, respectively.

Similarly, Jonin et al. also postulated a more optimal exergy based MPC for a building HVAC system, specifically developing a computationally efficient algorithm [55]. The chosen energy network considered an HVAC system including a Seasonal Thermal Energy Storage (STES) system connected to a solar panel, Space Heaters (SP), and Domestic Hot Water (DHW), applied to a simple house. A computationally efficient MPC was developed and solved using a Sequential Quadratic Programming (SQP) framework, which used exergy based principles as performance and design metrics. The computational efficiency of the controller was verified and used to analyze and design the energy system that achieved the minimal size of the STES, while meeting the demand requirements of the DHW and SP. The study illustrated how the use of exergy based principles could help to optimize system design.

Similar to Jonin, Baranski et al. focused on developing an algorithm suitable for optimizing a building supply chain HVAC [56]. The study considered a building HVAC system composed of warm storage, a heat pump, a boiler, and two separate rooms with Facade Ventilation Units (FVUs). Each component within the HVAC supply chain was classified as a subsystem and continually simplified when possible. The control policy then manipulated the base independent variables (mass flow rate, etc.) and gradually optimized the subsystem variables to minimize exergy destruction. This created a computationally efficient algorithm, as the subsystem decomposition led to a reduction in complexity. The computational efficiency of the MPC was high and presumed to arrive at a near global optimal solution. The algorithms made reasonable decisions and ensured stable operation. The benefit of the exergy based MPC was not investigated due to the selection of the case study.

However, Baranski et al. built on their initial algorithm to develop a simulation-assisted control of a building HVAC supply chain [59]. Using more detailed models, the algorithm was simulated using an open loop and closed loop configuration, in addition to a benchmark rule based feedback controller. The open loop controller had high tracking error, which could be minimized by adding a PI controller. The benchmark rule based controller out-preformed the open loop implementation, resulting from manual optimization of boundary conditions, without which fundamentally different systems would have been simulated. The closed loop controller worked better than the open loop controller, but was still outperformed by the benchmark.

Sayadi et al. in collaboration with Baranski then developed a set of exergy based control strategies for a building HVAC [60]. Three different case studies were developed. The first considered an office room with separate cooling and heating systems composed of a fan, hot and cold water mixing valves, heating and cooling coils, heating and cooling pumps, and an FVU. The second case study considered six decentralized ventilation units connected to one circulation pump and a three-way mixing valve. The third case study was based on Case Study 1 and extended to include a CHP. An MPC based control architecture was developed for the design of both local and supervisory level controllers. Both energy and exergy based controllers were developed. A rule based controller was also included for comparison. The results indicated that exergy was a universally applicable measure of controller performance for systems that are thermally controlled. The exergy based controllers reduced operation cost by 13% in one of the case studies, while a second illustrated the ability to implement model-assisted control. The final case study also indicated that the exergy based control could reduce energy demand up to 23.1% when compared to the standard rule based controller.

Sangi and Müller [61] subsequently tackled an exergy based control strategy using the same energy network of Sayadi et al.'s Case 3 [60]. However, Sangi and Müller developed their exergy based controller using a Multi-Agent System (MAS). They simulated the system using the MAS with and without MPC. The agents were assigned to each individual component and used to facilitate communication of measurement signals and the actuator control command signals between the local and supervisory level controllers. A mode based control was also developed as a benchmark used to assess the performance of the MAS. The benchmark outperformed the MAS when implemented without MPC. Thus, the agent based control was coupled with MPC. The combined agent based MPC improved stability, while reducing energy consumption, when compared to the agent based controller without MPC and the mode based control.

Similar to the instances in Table 1 where exergy is used for optimization, the authors contributing to the field of exergetic control typically do so in sectors where their work will have the greatest impact. Table 1 shows that 75% of the exergetic control work was focused on the area that uses, as Jonin et al. reported, up to 40% of the total energy consumed in the United States and Europe. Knowing that, it is clear that the focus of accomplished research is being conducted in areas that will potentially have the greatest impact. Since 1973, when Shell Oil implemented the first industrially viable MPC unit, the use of this technology grew exponentially. As of 2003, there were over 4600 instances of MPC implemented in industry to manage multi-variable control problems [97]. Because these results were only the results of a survey and it is known that many companies design and implement MPC under proprietary guidelines, this estimate was likely conservative and has continued to grow. Regardless, it is safe to assume that MPC is the current industry standard for multi-variable control problems, and the aforementioned survey by Qin and Badgwell stated that over 63% of all MPC algorithms are employed in that industry [97]. The refining of crude oil is an energy intensive process, currently accounting for at least 5.76% of energy use annually in the United States, which is 18% of all energy used for industrial processes in the country [95]. In contrast, these values were reported in 1976 as 4% and 15%, respectively [98]. A small improvement in efficiency in a heavily energy dependent industry that uses at least 63% of MPC algorithms, potentially through the introduction of exergy based control, could provide substantial efficiency improvements in the petroleum refining industry. For instance, if exergy based control were able to reduce energy consumption in refineries by 5% annually, that would be approximately 0.3 quads. This seemingly insignificant amount is actually significant based on the brief example described in Section 2 of this manuscript and would be an exciting improvement.

Due to the density of MPC in industry, especially in refineries, it seems that the time has arrived to take another step to gain substantial improvements in efficiency. Corporations use the best tools available to achieve efficiency for both profit and environmental stewardship, while the use of exergy as the currency for control and optimization has not yet become mainstream. With an increased awareness of the affects of waste and pollution over the past twenty years, it is unclear why this phenomena occurs. The next suite of innovative energy solutions, led by renewables, will benefit greatly from a movement towards exergy based process control.

5. Conclusions

This study compiled and reviewed the work of others in the area of exergy analysis, optimization, and control. The authors reported promising improvements when exergy was used for optimization and control, yet this study was focused on and demonstrated that there is still great opportunity to improve energy systems by utilizing exergy. The volume of publications focused on the analysis of IESs using exergy for improving efficiency is rather vast. This manuscript demonstrated that there is a clear shortage of research emphasis where optimization and control are applied and sought to maximize exergy or minimize the destruction of exergy. A great opportunity exists for researchers willing to explore this area and to establish trust and confidence in the ideas presented in the aforementioned manuscripts. The introduction and integration of increasing amounts of renewables, as well as increased emphasis on efficiency to negate the affects of climate change will drive research in this area. The potential exists to use current established processes with well studied and stable control loops to evaluate exergy based algorithms to determine definitively under what conditions and processes exergy can assist the control and optimization algorithms to improve efficiency.

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Reference

1. Pacheco, R.; Ordóñez, J.; Martínez, G. Energy efficient design of building: A review. *Renew. Sustain. Energy Rev.* **2012**, *16*, 3559–3573. [CrossRef]
2. Kalinci, Y.; Dincer, I.; Hepbasli, A. Energy and exergy analyses of a hybrid hydrogen energy system: A case study for Bozcaada. *Int. J. Hydrog. Energy* **2017**, *42*, 2492–2503. [CrossRef]
3. Dincer, I.; Cengel, Y. Energy, entropy and exergy concepts and their roles in thermal engineering. *Entropy* **2001**, *3*, 116–149. [CrossRef]
4. BoroumandJazi, G.; Saidur, R.; Rismanchi, B.; Mekhilef, S. A review on the relation between the energy and exergy efficiency analysis and the technical characteristic of the renewable energy systems. *Renew. Sustain. Energy Rev.* **2012**, *16*, 3131–3135. [CrossRef]
5. Saidur, R.; Abdul Khaliq, A.; Masjuki, H.H. Analysis of energy and exergy use for process heating in the industrial sector of Malaysia. *Int. J. Exergy* **2006**, *3*, 119–149. [CrossRef]
6. Jain, N. Thermodynamics Based Optimization and Control Of Integrated Energy Systems. Ph.D. Thesis, University of Illinois, Urbana-Champaign, IL, USA, 2013.
7. Gibbs, J.W. A Method of Geometrical Representation of the Thermodynamic Properties by Means of Surfaces. *Trans. Conn. Acad. Arts Sci.* **1873**, 382–404.
8. Rant, Z. Exergy, a new word for technical available work. *Forsch. Ing. Wis.* **1956**, *22*, 36–37.
9. Morris, D.R.; Szargut, J. Standard chemical exergy of some elements and compounds on the planet earth. *Energy* **1986**, *11*, 733–755. [CrossRef]
10. Szargut, J. Analysis of cumulative exergy consumption. *Int. J. Energy Res.* **1987**, *11*, 541–547. [CrossRef]
11. Szargut, J.; Morris, D.R. Cumulative exergy consumption and cumulative degree of perfection of chemical processes. *Int. J. Energy Res.* **1987**, *11*, 245–261. [CrossRef]
12. Szargut, J. Sequence method of determination of partial exergy losses in thermal systems. *Exergy Int. J.* **2001**, *1*, 85–90. [CrossRef]
13. Szargut, J.; Ziębik, A.; Stanek, W. Depletion of the non-renewable natural exergy resources as a measure of the ecological cost. *Energy Convers. Manag.* **2002**, *43*, 1149–1163. [CrossRef]
14. Szargut, J.T. Anthropogenic and natural exergy losses (exergy balance of the Earth's surface and atmosphere). *Energy* **2003**, *28*, 1047–1054. [CrossRef]
15. Szargut, J.; Szczygiel, I. Utilization of the cryogenic exergy of liquid natural gas (LNG) for the production of electricity. *Energy* **2009**, *34*, 827–837. [CrossRef]
16. Rivero, R.; Garfias, M. Standard chemical exergy of elements updated. *Energy* **2006**, *31*, 3310–3326. [CrossRef]

17. Szargut, J.; Morris, D. Cumulative exergy losses associated with the production of lead metal. *Int. J. Energy Res.* **1990**, *14*, 605–616. [CrossRef]
18. Szargut, J. Exergy in the thermal systems analysis. In *Thermodynamic Optimization of Complex Energy Systems*; Springer: Dordrecht, the Netherlands, 1999; pp. 137–150.
19. Szargut, J. Chemical exergies of the elements. *Appl. Energy* **1989**, *32*, 269–286. [CrossRef]
20. Szargut, J. Local and system exergy losses in cogeneration processes. *Int. J. Thermodyn.* **2007**, *10*, 135–142.
21. Szargut, J.; Morris, D.R.; Steward, F.R. *Exergy Analysis of Thermal, Chemical, and Metallurgical Processes*; U.S. Department of Energy: Washington, DC, USA, 1987.
22. Sorin, M.; Brodyansky, V. A method for thermodynamic optimization—I. Theory and application to an ammonia-synthesis plant. *Energy* **1992**, *17*, 1019–1031. [CrossRef]
23. Sorin, M.V.; Brodyansky, V.M.; Paris, J. Observations on exergy efficiency coefficients. In Proceedings of the Florence World Energy Research Symposium, Florence, Italy, 6–8 July 1994; SG Editoriali: Padova, Italy, 1994; Volume 94, pp. 941–949.
24. Sorin, M.; Brodyansky, V.; Paris, J. Thermodynamic Evaluation of a Distillation AES, Thermodynamics and the Design Analysis and Improvement of Energy Systems. *ASME* **1994**, *33*, 125–134.
25. Brodyansky, V.M.; Sorin, M.V.; Le Goff, P. *The Efficiency of Industrial Processes: Exergy Analysis and Optimization*; Elsevier: Amsterdam, The Netherlands, 1994; Volume 9.
26. Kotas, T.J. Exergy concepts for thermal plant: First of two papers on exergy techniques in thermal plant analysis. *Int. J. Heat Fluid Flow* **1980**, *2*, 105–114. [CrossRef]
27. Kotas, T.J. Exergy Criteria of Performance for Thermal Plant: Second of two papers on exergy techniques in thermal plant analysis. *Int. J. Heat Fluid Flow* **1980**, *2*, 147–163. [CrossRef]
28. Kotas, T.J. *The Exergy Method of Thermal Plant Analysis*; Elsevier: Amsterdam, The Netherlands, 2013.
29. U.S. Energy Information Agency. Available online: https://www.eia.gov/energyexplained/us-energy-facts/ (accessed on 3 February 2020).
30. Regulagadda, P.; Dincer, I.; Naterer, G. Exergy analysis of a thermal power plant with measured boiler and turbine losses. *Appl. Therm. Eng.* **2010**, *30*, 970–976. [CrossRef]
31. Ozden, E.; Tari, I. Energy—Exergy and economic analyses of a hybrid solar–hydrogen renewable energy system in Ankara, Turkey. *Appl. Therm. Eng.* **2016**, *99*, 169–178. [CrossRef]
32. Koroneos, C.J.; Fokaides, P.A.; Christoforou, E.A. Exergy analysis of a 300 MW lignite thermoelectric power plant. *Energy* **2014**, *75*, 304–311. [CrossRef]
33. Acar, C.; Dincer, I. Energy and exergy analyses of a novel photoelectrochemical hydrogen production system. *Int. J. Hydrog. Energy* **2017**, *42*, 30550–30558. [CrossRef]
34. Calderon, M.; Calderon, A.; Ramiro, A.; Gonzalez, J.; Gonzalez, I. Evaluation of a hybrid photovoltaic-wind system with hydrogen storage performance using exergy analysis. *Int. J. Hydrog. Energy* **2011**, *36*, 5751–5762. [CrossRef]
35. Exergy Based Analysis for the Environmental Control and Life Support Systems of the International Space Station. NASA Technical Reports Server. Available online: https://ntrs.nasa.gov/search.jsp?R=20160012079 (accessed on 3 February 2020).
36. Kaushik, S.; Reddy, V.S.; Tyagi, S. Energy and exergy analyses of thermal power plants: A review. *Renew. Sustain. Energy Rev.* **2011**, *15*, 1857–1872. [CrossRef]
37. Ozgener, O.; Hepbasli, A. A review on the energy and exergy analysis of solar assisted heat pump systems. *Renew. Sustain. Energy Rev.* **2007**, *11*, 482–496. [CrossRef]
38. Sayin, C.; Hosoz, M.; Canakci, M.; Kilicaslan, I. Energy and exergy analyses of a gasoline engine. *Int. J. Energy Res.* **2007**, *31*, 259–273. [CrossRef]
39. Al-Najem, N.; Diab, J. Energy-exergy analysis of a diesel engine. *Heat Recovery Syst. CHP* **1992**, *12*, 525–529. [CrossRef]
40. Bourhis, G.; Leduc, P. Energy and exergy balances for modern diesel and gasoline engines. *Oil Gas Sci. Technol. Rev.* **2010**, *65*, 39–46. [CrossRef]
41. Sorin, M.; Lambert, J.; Paris, J. Exergy flows analysis in chemical reactors. *Chem. Eng. Res. Des.* **1998**, *76*, 389–395. [CrossRef]
42. Sorin, M.; Paris, J. Combined exergy and pinch approach to process analysis. *Comput. Chem. Eng.* **1997**, *21*, S23–S28. [CrossRef]

43. Sorin, M.; Paris, J. Integrated exergy load distribution method and pinch analysis. *Comput. Chem. Eng.* **1999**, *23*, 497–507. [CrossRef]
44. Sorin, M.; Bonhivers, J.C.; Paris, J. Exergy efficiency and conversion of chemical reactions. *Energy Convers. Manag.* **1998**, *39*, 1863–1868. [CrossRef]
45. Sorin, M.; Hammache, A.; Diallo, O. Exergy based approach for process synthesis. *Energy* **2000**, *25*, 105–129. [CrossRef]
46. Douvartzides, S.; Coutelieris, F.; Tsiakaras, P. Exergy analysis of a solid oxide fuel cell power plant fed by either ethanol or methane. *J. Power Sour.* **2004**, *131*, 224–230. [CrossRef]
47. Douvartzides, S.; Coutelieris, F.; Tsiakaras, P. On the systematic optimization of ethanol fed SOFC based electricity generating systems in terms of energy and exergy. *J. Power Sour.* **2003**, *114*, 203–212. [CrossRef]
48. Song, S.; Douvartzides, S.; Tsiakaras, P. Exergy analysis of an ethanol fuelled proton exchange membrane (PEM) fuel cell system for automobile applications. *J. Power Sour.* **2005**, *145*, 502–514. [CrossRef]
49. Douvartzides, S.; Coutelieris, F.; Tsiakaras, P. Energy and exergy analysis of a solid oxide fuel cell plant fueled by ethanol and methane. *Ionics* **2003**, *9*, 293–296. [CrossRef]
50. Faramarz, S.; Said, F.; Hossein, A.; Amin, B. Exergetic optimization of a solar photovoltaic array. *J. Thermodyn.* **2010**, *2009*. [CrossRef]
51. Rosen, M.; Bulucea, C.A. Using exergy to understand and improve the efficiency of electrical power technologies. *Entropy* **2009**, *11*, 820–835. [CrossRef]
52. Razmara, M.; Maasoumy, M.; Shahbakhti, M.; Robinett, R., III. Optimal exergy control of building HVAC system. *Appl. Energy* **2015**, *156*, 555–565. [CrossRef]
53. Razmara, M.; Maasoumy, M.; Shahbakhti, M.; Robinett, R.D. Exergy based model predictive control for building HVAC systems. In Proceedings of the 2015 American Control Conference (ACC), Chicago, IL, USA, 1–3 July 2015; pp. 1677–1682.
54. Reddy, C.R.; Razmara, M.; Shahbakhti, M.; Robinett, R.D. Optimal Exergy-wise Predictive Control for a Combined MicroCSP and HVAC System in a Building. In Proceedings of the 2019 American Control Conference (ACC), Philadelphia, PA, USA, 10–12 July 2019; pp. 235–240.
55. Jonin, M.; Khosravi, M.; Eichler, A.; Villasmil, W.; Schuetz, P.; Jones, C.N.; Smith, R.S. Exergy based model predictive control for design and control of a seasonal thermal energy storage system. *J. Physics Conf. Ser.* **2019**, *1343*, 012066. [CrossRef]
56. Baranski, M.; Sangi, R.; Fütterer, J.; Müller, D. An Algorithm for Stepwise Exergy based Model Predictive Control of Building HVAC Supply Chains. In Proceedings of the ECOS, Portorož, Slovenia, 19–23 June 2016; pp. 19–23.
57. Liu, Z.; Chen, X.; Xu, X.; Guan, X. A decentralized optimization method for energy saving of HVAC systems. In Proceedings of the 2013 IEEE International Conference on Automation Science and Engineering (CASE), Madison, WI, USA, 17–20 August 2013; pp. 225–230.
58. Coffey, B. Using Building Simulation and Optimization to Calculate Lookup Tables for Control, 2012. Available online: https://digitalassets.lib.berkeley.edu/etd/ucb/text/Coffey_berkeley_0028E_12085.pdf (accessed on 3 February 2020)
59. Baranski, M.; Fütterer, J.; Müller, D. Distributed exergy based simulation-assisted control of HVAC supply chains. *Energy Build.* **2018**, *175*, 131–140. [CrossRef]
60. Sayadi, S.; Tsatsaronis, G.; Morosuk, T.; Baranski, M.; Sangi, R.; Müller, D. Exergy based control strategies for the efficient operation of building energy systems. *J. Clean. Prod.* **2019**, *241*, 118277. [CrossRef]
61. Sangi, R.; Müller, D. A novel hybrid agent based model predictive control for advanced building energy systems. *Energy Convers. Manag.* **2018**, *178*, 415–427. [CrossRef]
62. Trinklein, E.H.; Parker, G.G.; McCoy, T.J. Modeling, optimization, and control of ship energy systems using exergy methods. *Energy* **2020**, *191*, 116542. [CrossRef]
63. Jain, N.; Alleyne, A. Exergy based optimal control of a vapor compression system. *Energy Convers. Manag.* **2015**, *92*, 353–365. [CrossRef]
64. Salahshoor, K.; Asheri, M. A new exergy based model predictive control methodology for energy assessment and control. *J. Nat. Gas Sci. Eng.* **2014**, *21*, 489–495. [CrossRef]
65. Hadian, M.; Asheri, M.; Salahshoor, K. A novel exergy-event based model predictive control strategy for energy saving. *J. Nat. Gas Sci. Eng.* **2014**, *21*, 712–717. [CrossRef]

66. Ray, T.K.; Ganguly, R.; Gupta, A. Optimal control strategy for minimization of exergy destruction in boiler superheater. *Energy Convers. Manag.* **2013**, *66*, 234–245. [CrossRef]
67. Trinklein, E.H.; Cook, M.D.; Parker, G.G.; Weaver, W.W. Exergy optimal multi-physics aircraft microgrid control architecture. *Int. J. Electr. Power Energy Syst.* **2020**, *114*, 105403. [CrossRef]
68. Farahat, S.; Sarhaddi, F.; Ajam, H. Exergetic optimization of flat plate solar collectors. *Renew. Energy* **2009**, *34*, 1169–1174. [CrossRef]
69. Ajam, H.; Farahat, S.; Sarhaddi, F. Exergetic optimization of solar air heaters and comparison with energy analysis. *Int. J. Thermodyn.* **2005**, *8*, 183–190.
70. Sobhnamayan, F.; Sarhaddi, F.; Alavi, M.; Farahat, S.; Yazdanpanahi, J. Optimization of a solar photovoltaic thermal (PV/T) water collector based on exergy concept. *Renew. Energy* **2014**, *68*, 356–365. [CrossRef]
71. Sarhaddi, F.; Farahat, S.; Ajam, H.; Behzadmehr, A. Exergetic optimization of a solar photovoltaic thermal (PV/T) air collector. *Int. J. Energy Res.* **2011**, *35*, 813–827. [CrossRef]
72. Sarhaddi-student, F.; Farahat, S.; Ajam, H.; Sobhnamayan, F. Thermodynamic optimization of the solar parabolic cookers and comparison with energy analysis. In Proceedings of the Fifth International Chemical Engineering Congress (IchEC 2008), Tehran, Iran, 2–5 January 2008.
73. Naserian, M.M.; Farahat, S.; Sarhaddi, F. Exergoeconomic multi objective optimization and sensitivity analysis of a regenerative Brayton cycle. *Energy Convers. Manag.* **2016**, *117*, 95–105. [CrossRef]
74. Ashouri, M.; Ahmadi, M.H.; Pourkiaei, S.M.; Astaraei, F.R.; Ghasempour, R.; Ming, T.; Hemati, J.H. Exergy and exergo-economic analysis and optimization of a solar double pressure organic Rankine cycle. *Therm. Sci. Eng. Prog.* **2018**, *6*, 72–86. [CrossRef]
75. Behzadi, A.; Gholamian, E.; Ahmadi, P.; Habibollahzade, A.; Ashjaee, M. Energy, exergy and exergoeconomic (3E) analyses and multi-objective optimization of a solar and geothermal based integrated energy system. *Appl. Therm. Eng.* **2018**, *143*, 1011–1022. [CrossRef]
76. Ahmadi, M.H.; Mehrpooya, M.; Pourfayaz, F. Thermodynamic and exergy analysis and optimization of a transcritical CO2 power cycle driven by geothermal energy with liquefied natural gas as its heat sink. *Appl. Therm. Eng.* **2016**, *109*, 640–652. [CrossRef]
77. Ahmadi, M.H.; Ahmadi, M.A.; Sadatsakkak, S.A. Thermodynamic analysis and performance optimization of irreversible Carnot refrigerator by using multi-objective evolutionary algorithms (MOEAs). *Renew. Sustain. Energy Rev.* **2015**, *51*, 1055–1070. [CrossRef]
78. Ahmadi, M.H.; Ahmadi, M.A.; Pourfayaz, F.; Bidi, M.; Açıkkalp, E. Multi-objective optimization and exergetic-sustainability of an irreversible nano scale Braysson cycle operating with Maxwell–Boltzmann gas. *Alex. Eng. J.* **2016**, *55*, 1785–1798. [CrossRef]
79. Boyaghchi, F.A.; Chavoshi, M. Multi-criteria optimization of a micro solar-geothermal CCHP system applying water/CuO nanofluid based on exergy, exergoeconomic and exergoenvironmental concepts. *Appl. Therm. Eng.* **2017**, *112*, 660–675. [CrossRef]
80. Boyaghchi, F.A.; Sabaghian, M. Multi objective optimisation of a Kalina power cycle integrated with parabolic trough solar collectors based on exergy and exergoeconomic concept. *Int. J. Energy Technol. Policy* **2016**, *12*, 154–180. [CrossRef]
81. Ahmadi, P.; Dincer, I. Exergoenvironmental analysis and optimization of a cogeneration plant system using Multimodal Genetic Algorithm (MGA). *Energy* **2010**, *35*, 5161–5172. [CrossRef]
82. Ahmadi, P.; Dincer, I. Thermodynamic and exergoenvironmental analyses, and multi-objective optimization of a gas turbine power plant. *Appl. Therm. Eng.* **2011**, *31*, 2529–2540. [CrossRef]
83. Barzegar Avval, H.; Ahmadi, P.; Ghaffarizadeh, A.; Saidi, M. Thermo-economic-environmental multiobjective optimization of a gas turbine power plant with preheater using evolutionary algorithm. *Int. J. Energy Res.* **2011**, *35*, 389–403. [CrossRef]
84. Shamoushaki, M.; Ghanatir, F.; Ehyaei, M.; Ahmadi, A. Exergy and exergoeconomic analysis and multi-objective optimisation of gas turbine power plant by evolutionary algorithms. Case study: Aliabad Katoul power plant. *Int. J. Exergy* **2017**, *22*, 279–307. [CrossRef]
85. Boait, P.; Rylatt, R.; Wright, A. Exergy based control of electricity demand and microgeneration. *Appl. Energy* **2007**, *84*, 239–253. [CrossRef]
86. Ahmadi, P.; Rosen, M.A.; Dincer, I. Multi-objective exergy based optimization of a polygeneration energy system using an evolutionary algorithm. *Energy* **2012**, *46*, 21–31. [CrossRef]

87. Ahmadi, P.; Dincer, I.; Rosen, M.A. Exergy, exergoeconomic and environmental analyses and evolutionary algorithm based multi-objective optimization of combined cycle power plants. *Energy* **2011**, *36*, 5886–5898. [CrossRef]
88. Ahmadi, P.; Dincer, I.; Rosen, M.A. Thermodynamic modeling and multi-objective evolutionary based optimization of a new multigeneration energy system. *Energy Convers. Manag.* **2013**, *76*, 282–300. [CrossRef]
89. Ahmadi, P.; Dincer, I.; Rosen, M.A. Performance assessment and optimization of a novel integrated multigeneration system for residential buildings. *Energy Build.* **2013**, *67*, 568–578. [CrossRef]
90. Kilkis, B.I.; Kilkis, S. Exergetic Optimization of Generated Electric Power Split in a Heat Pump Coupled Poly-Generation System. In Proceedings of the ASME 2007 Energy Sustainability Conference, Long Beach, CA, USA, 27–30 July 2007; pp. 211–218.
91. Hajabdollahi, H.; Ahmadi, P.; Dincer, I. An exergy based multi-objective optimization of a heat recovery steam generator (HRSG) in a combined cycle power plant (CCPP) using evolutionary algorithm. *Int. J. Green Energy* **2011**, *8*, 44–64. [CrossRef]
92. Hajabdollahi, H.; Ahmadi, P.; Dincer, I. Exergetic optimization of shell-and-tube heat exchangers using NSGA-II. *Heat Transf. Eng.* **2012**, *33*, 618–628. [CrossRef]
93. Mozafari, A.; Ahmadi, A.; Ehyaei, M. Optimisation of micro gas turbine by exergy, economic and environmental (3E) analysis. *Int. J. Exergy* **2010**, *7*, 1–19. [CrossRef]
94. Razmara, M.; Bidarvatan, M.; Shahbakhti, M.; Robinett III, R. Optimal exergy based control of internal combustion engines. *Appl. Energy* **2016**, *183*, 1389–1403. [CrossRef]
95. U.S. Energy Information Agency. Available online: https://www.eia.gov/energyexplained/use-of-energy/industry.php (accessed on 3 February 2020).
96. U.S. Energy Information Agency. Available online: https://www.eia.gov/todayinenergy/detail.php?id=42497 (accessed on 3 February 2020).
97. Qin, S.J.; Badgwell, T.A. A survey of industrial model predictive control technology. *Control. Eng. Pract.* **2003**, *11*, 733–764. [CrossRef]
98. Haynes, V. *Energy Use in Petroleum Refineries*; Technical report; Oak Ridge National Laboratory: Oak Ridge, TN, USA, 1976.