

MULTIOBJECTIVE OPTIMIZATION OF ENERGY AND ROUTING PROBLEMS

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by

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I would like to dedicate this thesis to my parents and husband.

Certificate

This is to certify that the thesis titled “**Multiobjective Optimization of Energy and Routing Problems**” being submitted by Ms. Anubha Agrawal in the Department of Chemical Engineering, Indian Institute of Technology Delhi, for the award of the degree of Doctor of Philosophy, in Chemical Engineering, is a record of the original, bonafide research work carried out by her under my guidance and supervision. In my opinion, the thesis has reached the standards fulfilling the requirements of the regulations relating to the degree. The results contained in this thesis have not been submitted for the award of any other degree, associateship or similar title of any university or institute.

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Abstract

Energy transition, agricultural development, e-commerce growth, and safe maritime transportation are essential for the unprecedented economic growth of many developing nations like India. The sustainable growth of these sectors is possible by moving towards the sustainable development goals (SDGs) adopted by United Nations member states in 2015, including basic resources to all (SDG 1), sustainable agriculture (SDG 2), good health (SDG 3), water security (SDG 6), clean energy generation (SDG 7), economic growth (SDG 8), responsible consumption (SDG 12), mitigate climate change (SDG 13), marine security (SDG 14), land use (SDG 15), security sector (SDG 16), and inter-regional collaboration (SDG 17). In 2021, about 36 % of global electricity demands are met by coal-fired power plants, which accounts for the consumption of 65% of global coal available. The resulting CO₂ emissions are about 10.5 gigatonnes, attributed to 29% of global energy-related CO₂ emissions. Unfortunately, India is positioned as the world's 3rd largest greenhouse gas emitter due to ~60 % of its electricity demands being met through coal power plants. The pollution from coal power plants causes around 100,000 premature mortalities annually. Further, they consume and require large amounts of water. To overcome these issues, renewable energy resources such as solar and wind are installed, bringing India to rank 3rd in renewable installation. However, they depend on the weather conditions, may require ample space for installation, and are costly. This poses the requirement for a sustainable energy system through economic, social, and ecological dimensions. A grid-connected renewables integrated energy system (RIES) comprised of solar PV modules, wind turbines, Hydrogen fuel cells, and a coal power plant is proposed to meet the power demands of high-income Indian households. It is optimized to obtain the best trade-off between costs to the company, society, and ecosystem for three differentially populated regions of India. A significant reduction in mortalities and ecological degradation is achievable, along with a decrease in electricity cost using optimized RIES, particularly for populated cities. The optimized designs show a more significant reduction in mortalities than the base case and electricity cost of INR 4.72-5.25/kWh. Further, it has been found that the benefits of optimized RIES in terms of reducing greenhouse gas emissions and reducing human mortalities are highest in densely populated regions, which coincidentally suffer from worse air quality.

Furthermore, the escalating demand for clean energy has highlighted the potential of bioenergy, specifically energy generated from crop residue. Instead of leaving a large amount

of crop residue to decompose or be burned in the fields, which can contribute to air pollution and greenhouse gas emissions, it can be collected and used as a valuable energy resource. It offers an opportunity for farmers to diversify their income streams by selling their crop residue as a feedstock for bioenergy production or producing their bioenergy on-site. Since the demands of food, energy, water, and land are increasing with increased population, it is vital to utilize the land efficiently so as to fulfill the food and energy demands simultaneously while minimizing water consumption. Considering the agricultural sector as the central point, the mathematical model of the energy system is proposed and optimized to maximize the food production and bioenergy benefits while minimizing water consumption, through land allocation. This study has been conducted in three regions of India to understand the interplay of various factors. Further, dietary constraints to ensure the production of staple foods (wheat and rice) and nutritional requirements are imposed while focusing on all the objectives. The results demonstrated up to a 1000 % increment in food production benefits, up to 4740 % increase in bioenergy benefits, and up to 97 % reduction in water consumption, compared to the base case in the single objective studies, yielding a win-win-win solution. Notably, our strategy allows the production of a variety of food crops while not putting pressure on any of the regions, in addition to contributing towards cleaner energy pathways and intelligent utilization of resources such as land and water while not compromising the economic benefits to the stakeholders.

The 14th SDG focuses on the sustainable use of marine resources in order to prevent illegal fishing activities and mitigate climate change. Globally, about 1.8 billion metric tons of crude oil get transported by sea every year. Further, India's international trade of about 95 % by volume and 70 % by value is carried through maritime transportation. However, there exist security and safety challenges in these sectors, e.g., smuggling of illicit goods, illegal fishing, human trafficking and robbery in maritime transportation. Therefore, it becomes quite essential to grow these sectors in a sustainable manner which refers to a balance between the economy, society, and environment. In the present work, multiobjective route optimization algorithms are developed and employed to surveillance marine vessels using Helideck Monitoring System (HMS) to prevent such illegal activities. These algorithms also find application in vehicle routing delivery in the fastest-growing e-commerce sector and planning and scheduling in chemical and petrochemical process industries. To optimize maritime surveillance using HMS, the mathematical model is formulated in terms of the traveling salesman problem (TSP) and is optimized to monitor the ships to prevent illegal activities in the blue economy. Though several local-heuristic-based algorithms are quite efficient in solving the single objective TSPs, the

efficacy of their extensions for solving the multiobjective and large-sized TSPs is limited. Therefore, a two-stage evolutionary algorithm (TSEA) is developed in the present work to solve the classical multiobjective TSP to minimize the tour length of a salesman in various planes. The algorithm is tested on 25 multiobjective benchmark problems, including two, three, and four objectives to test its efficacy on large-sized problems, i.e., 10000 cities/targets. The performance of TSEA is found to be better than the other compared algorithms. Further, the TSEA is modified by incorporating dynamic components such as position coordinates and the k -means clustering approach. This dynamic TSEA is applied in maritime surveillance using HMS. The efficient route for HMS to monitor the vessels is obtained by minimizing its tour length while prioritizing visiting the faulty (anomaly) vessel by applying the dynamic TSEA. Overall, the multiobjective optimization frameworks proposed in this study address many crucial problems that are essential for the growth of a nation's economy and have a significant contribution to the 1st, 2nd, 3rd, 6th, 7th, 8th, 12th, 13th, 14th, 15th, 16th and 17th SDGs.

सार

भारत जैसे कई विकासशील देशों की अभूतपूर्व आर्थिक वृद्धि के लिए ऊर्जा परिवर्तन, कृषि विकास, ई-कॉमर्स विकास और सुरक्षित समुद्री परिवहन आवश्यक हैं। 2015 में संयुक्त राष्ट्र के सदस्य देशों द्वारा अपनाए गए सतत विकास लक्ष्यों (एसडीजी) की ओर बढ़ने से इन क्षेत्रों का सतत विकास संभव है, जिसमें सभी के लिए बुनियादी संसाधन (एसडीजी 1), टिकाऊ कृषि (एसडीजी 2), अच्छा स्वास्थ्य (एसडीजी 3), जल सुरक्षा (एसडीजी 6), स्वच्छ ऊर्जा उत्पादन (एसडीजी 7), आर्थिक विकास (एसडीजी 8), जिम्मेदार उपभोग (एसडीजी 12), जलवायु परिवर्तन को कम करना (एसडीजी 13), समुद्री सुरक्षा (एसडीजी 14), भूमि उपयोग (एसडीजी 1) शामिल हैं। 5), सुरक्षा क्षेत्र (एसडीजी 16), और अंतर-क्षेत्रीय सहयोग (एसडीजी 17)। 2021 में, वैश्विक बिजली की लगभग 36% मांग कोयला आधारित बिजली संयंत्रों द्वारा पूरी की जाती है, जो उपलब्ध वैश्विक कोयले की 65% खपत के लिए जिम्मेदार है। परिणामी CO₂ उत्सर्जन लगभग 10.5 गीगाटन है, जो वैश्विक ऊर्जा-संबंधित CO₂ उत्सर्जन का 29% है। दुर्भाग्य से, भारत दुनिया के तीसरे सबसे बड़े ग्रीनहाउस गैस उत्सर्जक के रूप में स्थित है क्योंकि इसकी लगभग 60% बिजली की मांग कोयला बिजली संयंत्रों के माध्यम से पूरी होती है। कोयला बिजली संयंत्रों से निकलने वाले प्रदूषण के कारण प्रतिवर्ष लगभग 100,000 लोगों की असामयिक मृत्यु हो जाती है। इसके अलावा, वे बड़ी मात्रा में पानी का उपभोग और आवश्यकता करते हैं। इन मुद्दों को दूर करने के लिए, सौर और पवन जैसे नवीकरणीय ऊर्जा संसाधनों को स्थापित किया गया है, जिससे भारत नवीकरणीय स्थापना में तीसरे स्थान पर आ गया है। हालाँकि, वे मौसम की स्थिति पर निर्भर करते हैं, स्थापना के लिए पर्याप्त जगह की आवश्यकता हो सकती है, और महंगे हैं। यह आर्थिक, सामाजिक और पारिस्थितिक आयामों के माध्यम से एक स्थायी ऊर्जा प्रणाली की आवश्यकता को प्रस्तुत करता है। उच्च आय वाले भारतीय घरों की बिजली मांगों को पूरा करने के लिए सौर पीवी मॉड्यूल, पवन टरबाइन, हाइड्रोजन ईंधन सेल और एक कोयला बिजली संयंत्र से युक्त एक ग्रिड-कनेक्टेड नवीकरणीय एकीकृत ऊर्जा प्रणाली (आरआईईएस) प्रस्तावित है। इसे भारत के तीन अलग-अलग आबादी वाले क्षेत्रों के लिए कंपनी, समाज और पारिस्थितिकी तंत्र की लागत के बीच सर्वोत्तम व्यापार-बंद प्राप्त करने के लिए अनुकूलित किया गया है। विशेष रूप से आबादी वाले शहरों के लिए अनुकूलित आरआईईएस का उपयोग करके बिजली की लागत में कमी के साथ-साथ मृत्यु दर और पारिस्थितिक क्षरण में महत्वपूर्ण कमी प्राप्त की जा सकती है। अनुकूलित डिज़ाइन बेस केस और बिजली लागत 4.72-5.25/kWh की तुलना में मृत्यु दर में अधिक महत्वपूर्ण कमी दिखाते हैं। इसके अलावा, यह पाया गया है कि ग्रीनहाउस गैस उत्सर्जन को कम करने और मानव मृत्यु दर को कम करने के मामले में अनुकूलित आरआईईएस का लाभ घनी आबादी वाले क्षेत्रों में सबसे अधिक है, जो संयोग से बदतर वायु गुणवत्ता से पीड़ित हैं।

इसके अलावा, स्वच्छ ऊर्जा की बढ़ती मांग ने जैव ऊर्जा, विशेष रूप से फसल अवशेषों से उत्पन्न ऊर्जा की क्षमता को उजागर किया है। बड़ी मात्रा में फसल अवशेषों को सड़ने या जलाने के लिए खेतों में छोड़ने के बजाय, जो वायु

प्रदूषण और ग्रीनहाउस गैस उत्सर्जन में योगदान कर सकते हैं, इसे एकत्र किया जा सकता है और एक मूल्यवान ऊर्जा संसाधन के रूप में उपयोग किया जा सकता है। यह किसानों को अपने फसल अवशेषों को बायोएनर्जी उत्पादन के लिए फीडस्टॉक के रूप में बेचकर या साइट पर अपनी बायोएनर्जी का उत्पादन करके अपनी आय धाराओं में विविधता लाने का अवसर प्रदान करता है। चूंकि बढ़ती जनसंख्या के साथ भोजन, ऊर्जा, पानी और भूमि की माँगें बढ़ रही हैं, इसलिए भूमि का कुशलतापूर्वक उपयोग करना महत्वपूर्ण है ताकि पानी की खपत को कम करते हुए भोजन और ऊर्जा की माँगों को एक साथ पूरा किया जा सके। कृषि क्षेत्र को केंद्रीय बिंदु मानते हुए, ऊर्जा प्रणाली के गणितीय मॉडल को कृषि-आर्थिक खाद्य-ऊर्जा-जल-भूमि प्रणाली कहा जाता है, जिसे पानी की खपत को कम करते हुए खाद्य उत्पादन और बायोएनर्जी लाभों को अधिकतम करने के लिए प्रस्तावित और अनुकूलित किया जाता है। यह अध्ययन विभिन्न कारकों की परस्पर क्रिया को समझने के लिए भारत के तीन क्षेत्रों में आयोजित किया गया है। इसके अलावा, सभी उद्देश्यों पर ध्यान केंद्रित करते हुए मुख्य खाद्य पदार्थों (गेहूँ और चावल) के उत्पादन और पोषण संबंधी आवश्यकताओं को सुनिश्चित करने के लिए आहार संबंधी प्रतिबंध लगाए गए हैं। एकल उद्देश्य अध्ययन में आधार मामले की तुलना में, परिणामों ने खाद्य उत्पादन लाभों में 1000% की वृद्धि, बायोएनर्जी लाभों में 4740% तक की वृद्धि और पानी की खपत में 97% तक की कमी का प्रदर्शन किया, जिससे एक जीत-जीत समाधान प्राप्त हुआ। विशेष रूप से, हमारी रणनीति किसी भी क्षेत्र पर दबाव न डालते हुए विभिन्न प्रकार की खाद्य फसलों के उत्पादन की अनुमति देती है, इसके अलावा हितधारकों को आर्थिक लाभ से समझौता किए बिना स्वच्छ ऊर्जा मार्गों और भूमि और पानी जैसे संसाधनों के बुद्धिमान उपयोग में योगदान देती है।

14वां एसडीजी अवैध मछली पकड़ने की गतिविधियों को रोकने और जलवायु परिवर्तन को कम करने के लिए समुद्री संसाधनों के सतत उपयोग पर केंद्रित है। वैश्विक स्तर पर, हर साल लगभग 1.8 बिलियन मीट्रिक टन कच्चे तेल का परिवहन समुद्र के द्वारा किया जाता है। इसके अलावा, भारत का अंतर्राष्ट्रीय व्यापार मात्रा के हिसाब से लगभग 95% और मूल्य के हिसाब से 70% समुद्री परिवहन के माध्यम से होता है। हालाँकि, इन क्षेत्रों में सुरक्षा और सुरक्षा चुनौतियाँ मौजूद हैं, जैसे, अवैध वस्तुओं की तस्करी, अवैध मछली पकड़ना, मानव तस्करी और समुद्री परिवहन में डकैती, ग्लोबल वार्मिंग, पारिस्थितिक संसाधनों का शोषण और वर्तमान ऊर्जा प्रणालियों में मानव स्वास्थ्य क्षति। इसलिए, इन क्षेत्रों को टिकाऊ तरीके से विकसित करना काफी आवश्यक हो जाता है, जिसका तात्पर्य अर्थव्यवस्था, समाज और पर्यावरण के बीच संतुलन से है। वर्तमान कार्य में, डकैती और अस्थिर मछली पकड़ने जैसी अवैध गतिविधियों को रोकने के लिए हेलिडेक मॉनिटरिंग सिस्टम (एचएमएस) का उपयोग करके समुद्री जहाजों की निगरानी के लिए बहुउद्देश्यीय मार्ग अनुकूलन एल्गोरिदम विकसित और नियोजित किए गए हैं। ये एल्गोरिदम सबसे तेजी से बढ़ते ई-कॉमर्स क्षेत्र में वाहन रूटिंग डिलीवरी और रासायनिक और पेट्रोकेमिकल प्रक्रिया उद्योगों में योजना और शेड्यूलिंग में भी आवेदन पाते हैं। एचएमएस का उपयोग करके समुद्री निगरानी को अनुकूलित करने के लिए, गणितीय मॉडल ट्रैवलिंग सेल्समैन समस्या (टीएसपी) के संदर्भ में तैयार किया गया है और नीली अर्थव्यवस्था में अवैध गतिविधियों को रोकने के लिए जहाजों की निगरानी करने के लिए अनुकूलित किया गया है। यद्यपि कई स्थानीय-अनुमान-आधारित एल्गोरिदम एकल उद्देश्य टीएसपी को हल करने में काफी कुशल

हैं, बहुउद्देश्यीय और बड़े आकार के टीएसपी को हल करने के लिए उनके एक्सटेंशन की प्रभावकारिता सीमित है। इसलिए, विभिन्न स्तरों पर एक सेल्समैन की यात्रा की लंबाई को कम करने के लिए शास्त्रीय बहुउद्देश्यीय टीएसपी को हल करने के लिए वर्तमान कार्य में एक दो-चरण विकासवादी एल्गोरिदम (टीएसईए) विकसित किया गया है। एल्गोरिदम का परीक्षण 25 बहुउद्देश्यीय बेंचमार्क समस्याओं पर किया जाता है, जिसमें बड़े आकार की समस्याओं, यानी 10000 शहरों/लक्ष्यों पर इसकी प्रभावकारिता का परीक्षण करने के लिए दो, तीन और चार उद्देश्य शामिल हैं। टीएसईए का प्रदर्शन अन्य तुलनात्मक एल्गोरिदम से बेहतर पाया गया है। इसके अलावा, TSEA को स्थिति निर्देशांक और k-मीन्स क्लस्टरिंग दृष्टिकोण जैसे गतिशील घटकों को शामिल करके संशोधित किया गया है। इस गतिशील TSEA को HMS का उपयोग करके समुद्री निगरानी में लागू किया जाता है। जहाजों की निगरानी के लिए एचएमएस के लिए कुशल मार्ग गतिशील टीएसईए लागू करके दोषपूर्ण (विसंगति) जहाज का दौरा करने को प्राथमिकता देते हुए इसके दौरे की लंबाई को कम करके प्राप्त किया जाता है।

कुल मिलाकर, इस अध्ययन में प्रस्तावित बहुउद्देश्यीय अनुकूलन ढाँचे कई महत्वपूर्ण समस्याओं का समाधान करते हैं जो देश की अर्थव्यवस्था के विकास के लिए आवश्यक हैं और 1, 2, 3, 6, 7, 8, 12, 13, 14, 15, 16 और 17 एसडीजी में महत्वपूर्ण योगदान देते हैं।

Table of Contents

| | |
|--|-----------|
| Acknowledgments | i |
| Abstract | iii |
| List of Tables | xii |
| List of Figures | xiv |
| Chapter 1 | |
| Introduction | 1 |
| 1.1 Sustainable Energy Systems | 1 |
| 1.2 Route Optimization..... | 2 |
| 1.3 Research Objectives..... | 4 |
| 1.4 Outline of Thesis..... | 5 |
| Chapter 2 | |
| Renewables Integrated Energy Systems Can Provide Electricity at Lower Cost with Less Environmental and Social Damage | 8 |
| 2.1 Background and Motivation | 8 |
| 2.2 System of Interest | 14 |
| 2.2.1 System Description..... | 14 |
| 2.2.2 System Data..... | 17 |
| 2.2.3 Model Components..... | 20 |
| 2.3 Problem Formulation | 25 |
| 2.4 Results and Discussion | 29 |
| 2.5 Summary..... | 45 |
| Chapter 3 | |
| Optimal Land Allocation of the Crops can Help to Attain Food Nutrition and Cleaner Energy Pathways with Minimum Water | 47 |
| 3.1 Background and Motivation | 47 |
| 3.2 System of Interest | 51 |
| 2.2.1 System Description..... | 51 |
| 2.2.2 System Boundary..... | 52 |
| 2.2.3 System Data..... | 53 |
| 3.3 Problem Formulation | 57 |
| 3.4 Results and Discussion | 58 |

| | |
|-------------------|----|
| 3.5 Summary | 79 |
|-------------------|----|

Chapter 4

Evolutionary Algorithm Hybridized with Local Search and Intelligent Seeding for solving Multi-Objective Euclidian TSP 83

| | |
|---|-----|
| 4.1 Background and Motivation | 83 |
| 4.2 Problem Formulation | 88 |
| 4.3 Methodology | |
| 4.3.1 Initialization..... | 90 |
| 4.3.2 Non-Dominated Ranking..... | 92 |
| 4.3.3 Guided Crossover | 94 |
| 4.3.4 Guided Mutation..... | 97 |
| 4.3.5 Elitism..... | 100 |
| 4.3.6 Computational Complexity of HLS-EA | 100 |
| 4.3.7 Parameter Tuning of HLS-EA..... | 101 |
| 4.4 Results and Discussion | 104 |
| 4.4.1 Validation of HLS-EA on Single Objective ETSPs | 104 |
| 4.4.2 Comparison of TSEA with HLS-EA for Multiobjective ETSPs..... | 105 |
| 4.4.3 Comparison of TSEA with other Multiobjective Algorithms | 108 |
| 4.5 Summary | 124 |

Chapter 5

Traveling of Multiple Salesman to Dynamically Changing Locations for Satisfying Multiple Goals 126

| | |
|--|-----|
| 5.1 Background and Motivation | 126 |
| 5.2 Problem Formulation | 128 |
| 5.2.1 Dynamic Components in the TSEA | 131 |
| 5.2.2 Multiobjective Multiple Salesman Problem Formulation | 132 |
| 5.3 Methodology | 133 |
| 5.4 Results and Discussion | 137 |
| 5.4.1 DMOTSP..... | 137 |
| 5.4.2 DMOMTSP | 141 |
| 5.4.3 Very Large-sized TSP | 145 |
| 5.4.4 Case Study: Maritime Surveillance using HMS | 146 |

5.5 Summary..... 148

Chapter 6

Conclusions and Recommendations..... 149

6.1 Conclusions..... 149

6.2 Recommendations for Future Work..... 151

References..... 154

LIST OF TABLES

| | |
|--|----|
| Table 2.1 Impact of various energy sources on electricity cost, health cost, land use, and water use..... | 10 |
| Table 2.2 Review of multi-objective optimization studies accounting for environmental, social, and ecological impacts of HRES..... | 13 |
| Table 2.3 Population and DALY specific to air pollution for three locations in India..... | 17 |
| Table 2.4 Electricity mix at three different regions from current energy sources in India..... | 19 |
| Table 2.5 LCOE for various energy sources and their corresponding water equipment, land requirement and direct CO ₂ equivalent emissions..... | 20 |
| Table 2.6 Concentration of various pollutants from coal power plants and SMR with their relative risks..... | 21 |
| Table 2.7 Parameters of RIES components..... | 24 |
| Table 3.1 Cropping season, yield and land occupancy in the districts, Sangrur (Punjab), Wardha (Maharashtra), and Rewa (Madhya Pradesh), and crop residue ratio (CRR) and minimum support price (MSP), for all the crops..... | 54 |
| Table 3.2 Nutritional values include the calories, carbohydrates, proteins, and fats of the major crops per 100 grams..... | 55 |
| Table 3.3 Percentage total of carbohydrates, proteins, and fats of the major crops per 100 grams, in the base case at Punjab, Maharashtra, and Madhya Pradesh..... | 57 |
| Table 3.4 Region-wise comparison of all the corner solutions and operating points in monsoon and winter seasons for Case III..... | 72 |
| Table 3.5 Comparison of Case II and Case III results combined, with Case I in all three regions in the monsoon and winter seasons..... | 73 |

| | |
|---|-----|
| Table 4.1 Comparison of hypervolume, spacing, the fraction (L/N_p) of non-dominating solutions in the population, and CPU times using TSEA with different hybrid algorithms..... | 110 |
| Table 4.2 Comparison of TSEA with di_lk_a , di_lk_p , and 2PPLS for two-objective TSP..... | 113 |
| Table 4.3 Comparison of TSEA with di_lk_a , di_lk_p , and 2PPLS of three- and four-objective TSP..... | 114 |
| Table 4.4 Comparison of results of HLS-EA averaged over 10 runs [Av. Value \pm SD] with optimal results of ETSPs reported in TSPLIB..... | 116 |
| Table 4.5 Comparison of tour distances obtained using HLS-EA and several GA variants for reported TSPLIB problems..... | 117 |
| Table 4.6 Comparison of tour distances obtained using HLS-EA, PSO, ACO and HPSACO for reported TSPLIB problems..... | 119 |
| Table 4.7 Statistical results using Wilcoxon test..... | 119 |
| Table 4.8 Hypervolume results of 25 instances solved by TSEA..... | 121 |
| Table 4.9 CPU times of all kinds of two, three and four-objective instances solved by TSEA, di_lk_a , di_lk_p , and 2PPLS..... | 122 |
| Table 4.10 Hypervolume, Spacing and L/N_p for KROBE100 and KRODE100 for 200 Generations..... | 123 |
| Table 5.1 Comparison of hypervolumes of Kro problems using di_lk_a and di_lk_p and TSEA..... | 133 |

LIST OF FIGURES

| | |
|--|----|
| Figure 2.1 A grid-connected renewables integrated energy system (RIES)..... | 15 |
| Figure 2.2 24-hour profiles of (a) High-income household load profile for normal operation and 10 % higher load for the uncertain operation of 100 households and (b) solar irradiance, and (c) wind speed at three different regions..... | 18 |
| Figure 2.3. Three differentially populated regions of India: Vadodara, Badarpur and Jamnipali, are considered for case studies..... | 19 |
| Figure 2.4 (a) Pareto optimal solutions obtained for minimizing cost to company, cost to society, and cost to ecosystem, simultaneously for Vadodara..... | 31 |
| Figure 2.5 (a) Pareto optimal solutions obtained for minimizing cost to company, cost to society, and cost to ecosystem, simultaneously for Badarpur..... | 32 |
| Figure 2.6 (a) Pareto optimal solutions obtained for minimizing cost to company, cost to society, and cost to ecosystem, simultaneously for Jamnipali..... | 34 |
| Figure 2.7 Analysis of cost to company, cost to society, and cost to ecosystem corresponding to corner solutions ('C', 'S', and 'E'), operating point ('O') as shown in Figure 2.4 (a), and base case, in Vadodara..... | 35 |
| Figure 2.8 Analysis of cost to company, cost to society, and cost to ecosystem corresponding to corner solutions ('C', 'S', and 'E'), operating point ('O') and base case shown in Figure 2.5 (a). | 36 |
| Figure 2.9 Analysis of cost to company, cost to society, and cost to ecosystem corresponding to corner solutions ('C', 'S', and 'E'), operating point ('O') and base case shown in Figure 2.6 (a). | 37 |
| Figure 2.10 (a) Comparison of annual mortalities for the base case, RIES operating solution (RIES-O), RIES with minimum electricity cost (RIES-C), RIES with minimum health cost (RIES-S), and RIES with minimum ecological costs (RIES-E) for case 1, case 2, and case 3. (b) Comparison of electricity cost for the base case, RIES-O, RIES-C, RIES-S and RIES-E for case 1, case 2, and case 3. | 39 |

| | |
|---|----|
| Figure 2.11 (a – c) Pareto optimal fronts representing the 24 hours averaged cost to company, society and ecosystem for the scenario considering the capacity utilization factor of 23 % and 35 % for solar and wind power, respectively and (d – f) 24-hours averaged energy mix corresponding to solutions ‘C’, ‘S’, ‘E’ and ‘O’ on the Pareto fronts for Vadodara, Badarpur and Jamnipali..... | 41 |
| Figure 2.12 (a – c) Pareto optimal fronts representing the 24 hours averaged cost to company, society and ecosystem for the scenario considering the capacity utilization factor of 23 % and 35 % for solar and wind power, respectively along with 100 kW coal power plant capacity to meet the uncertain demand (shown in Figure. 2.2 (a)) and (d – f) 24-hours averaged energy mix corresponding to solutions ‘C’, ‘S’, ‘E’ and ‘O’ on the Pareto fronts for Vadodara, Badarpur and Jamnipali. | 42 |
| Figure 3.1 A representation of a multi-objective optimization framework for land allocation to various crops. | 54 |
| Figure 3.2 (a) Virtual water content (w) and (b) production cost (P_{π}), for all the crops at Sangrur (Punjab), Wardha (Maharashtra), and Rewa (Madhya Pradesh)..... | 56 |
| Figure 3.3 Optimal percentage allocation of land for different crops in the monsoon season for Case I (unconstrained), Case II (involving nutritional constraints to satisfy carbohydrate, protein, and fat requirements), Case III (involving nutritional and dietary constraints which additionally require to satisfy cereals, pulses, and oilseeds requirements), and base case scenario in (a) Punjab, (b) Maharashtra and (c) Madhya Pradesh..... | 65 |
| Figure 3.4 Optimal percentage allocation of land for different crops in the winter season for Case I (unconstrained), Case II (involving nutritional constraints to satisfy carbohydrate, protein, and fat requirements), Case III (involving nutritional and dietary constraints which additionally require to satisfy cereals, pulses, and oilseeds requirements), and base case scenario in (a) Punjab, (b) Maharashtra and (c) Madhya Pradesh..... | 67 |
| Figure 3.5 Inter-regional and case-wise comparison of food production benefits, bioenergy benefits, and water consumption in the monsoon season. | 68 |
| Figure 3.6 Inter-regional and case-wise comparison of food production benefits, bioenergy benefits, and water consumption in the winter season..... | 68 |
| Figure 3.7 Optimal food production benefits (in INR) obtained in Punjab, Maharashtra, and Madhya Pradesh in the (a) monsoon and (b) winter seasons..... | 69 |

| | |
|--|-----|
| Figure 3.8 Optimal bioenergy benefits (in INR) obtained in Punjab, Maharashtra, and Madhya Pradesh in the (a) monsoon and (b) winter seasons. | 70 |
| Figure 3.9 Optimal water consumption (in m ³) obtained in Punjab, Maharashtra, and Madhya Pradesh in the (a) monsoon and (b) winter seasons. | 74 |
| Figure 3.10 Optimal food quantity (in kt) obtained in Punjab, Maharashtra, and Madhya Pradesh in the (a) monsoon and (b) winter seasons. | 75 |
| Figure 3.11 Optimal bioenergy quantity (in kWh) obtained in Punjab, Maharashtra, and Madhya Pradesh in the (a) monsoon and (b) winter seasons. | 76 |
| Figure 3.12 Pareto plots for all three cases and all three regions in the monsoon season. $f_{1,best}$, $f_{2,best}$ and $f_{3,best}$ represent the best value of food production benefits, bioenergy benefits and water consumption, respectively. | 77 |
| Figure 3.13 Pareto plots for all three cases and all three regions in the winter season. $f_{1,best}$, $f_{2,best}$ and $f_{3,best}$ represent the best value of food production benefits, bioenergy benefits and water consumption, respectively..... | 78 |
| Figure 4.1 (a) General flowchart of TSEA, and (b) a detailed flowchart of HLSEA..... | 91 |
| Figure 4.2 Locations of six cities are shown by the circles (distance between any two cities is Euclidian distance between the corresponding center of the circles and is as per visual appearance). | 93 |
| Figure 4.3 A chromosome of six cities generated with (a) random procedure and (b) nearest neighbor heuristics..... | 93 |
| Figure 4.4 Guided Crossover operation illustrated with randomly obtained crossover site, $cross = 3$ | 96 |
| Figure 4.5 (a) Guided mutation illustrated for a six-city problem and (b) 2-opt move..... | 99 |
| Figure 4.6 Effect of variation in guided mutation probability on convergence and CPU time for problems rd 100 [(a) and (b), respectively] and random ETSP 2000 [(c) and (d), respectively]..... | 103 |

| | |
|---|-----|
| Figure 4.7 Pareto Plots of (a) KroAB100, (b) KroBC100, (c) KroBD100 and (d) KroAD100 (the utopia points are also shown by U)..... | 107 |
| Figure 4.8 Pareto Plots of (a) KroBE100 and (b) KroDE100 (total 200 generations, 25 gen for 2 single objectives and 150 for 2-objective)..... | 111 |
| Figure 4.9 Pareto Plots of multi-objective random ETSP with cities varying from 100, 500, 1000, 5000, and 10000 obtained using TSEA for 1000 generations..... | 115 |
| Figure 4.10 Pareto Plots of random three-objective ETSP with cities varying from 100, 500, 1000, 5000 and 10000 obtained using TSEA for 1000 generations. | 120 |
| Figure 5.1 Illustration of dynamic TSP | 130 |
| Figure 5.2 An end-to-end workflow of dynamic TSEA to solve DMOMTSP..... | 136 |
| Figure 5.3 Visualization of the instances in two planes for a multi-objective TSP. (a) Instances in plane 1, (b) Instances in plane 2 formed by mirroring plane 1, (c) Plane 2 with few exchanges of instances shown by two headed arrows and (d) Pareto optimal solutions of static and dynamic TSP for two-objectives in plane 1 and plane 2..... | 139 |
| Figure 5.4 Tours corresponding to the corner and best trade-off solutions presented in Fig.3 (d). (a), (b) Static and dynamic routes in plane 1 and plane 2 corresponding to the tour minimization of plane 1, (c), (d) Static and dynamic routes in plane 1 and plane 2 corresponding to the tour minimization of plane 2 and (e), (f) Static and dynamic routes in plane 1 and plane 2 corresponding to the best trade-off solution..... | 140 |
| Figure 5.5 Comparison of hypervolumes using dynamic HLSEA and dynamic TSEA..... | 141 |
| Figure 5.6 Visualization of the instances in two planes for the multi-objective multiple TSP. (a) Instances in plane 1, (b) Instances in plane 2 formed by mirroring plane 1 except two points retained as earlier and (c) Pareto optimal solutions of static and dynamic multiple TSPs for two-objectives in plane 1 and plane 2 and for four different clusters..... | 142 |
| Figure 5.7 Tours corresponding to the corner and best trade-off solutions presented in Fig.5.5 (c). (a), (b) Static and dynamic routes in plane 1 and plane 2 corresponding to DMOMTSP for minimizing the tour in plane 1, (c), (d) Static and dynamic routes in plane 1 and plane 2 corresponding to DMOMTSP for minimizing the tour in plane 2 and (e), (f) Static and dynamic routes in plane 1 and plane 2 corresponding to the best trade-off solution for DMOMTSP..... | 144 |

Figure 5.8 Pareto optimal solution for the large-scale dynamic TSP. (a) Normalized tour lengths in plane 1 and plane 2, for the two-objective dynamic TSP and (b) Normalized tour lengths in plane 1, plane 2 and plane 3, for the three-objective dynamic TSP.....146

Figure 5.9 Dynamic multi-objective TSP optimization for maritime surveillance by HMS. (a) Pareto plot for static and dynamic approach, (b) Tours corresponding to the best trade-off solutions depicted by enlarged triangle (Fig.5.8 (a)) for static and dynamic TSP on the Pareto plot and (c) Enlarged view of vessels under the red outlined area.....147