A SYSTEM ANALYSIS OF CONVERTING NON-RECYCLABLE PLASTIC WASTE INTO VALUE-ADDED PRODUCTS IN A PAPER INDUSTRY CLUSTER IN INDIA

by
Padmabhushana R. Desam

Doctor of Philosophy, Mechanical Engineering
University of Utah, Salt Lake City, 2006

Bachelor of Technology, Mechanical Engineering
National Institute of Technology, India, 1998

Submitted to the System Design and Management Program
in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Engineering and Management

at the

Massachusetts Institute of Technology

September 2013

Signature of author.. Signature redacted
System Design and Management Program
August 16, 2013

Certified by.............. Signature redacted ....
Charles H. Fine
Chrysler Leaders for Global Operations Professor of Management
MIT Sloan School of Management

Accepted by.......................... Signature redacted ....
Patrick Hale
Director
System Design and Management Program

This page is intentionally left blank

A SYSTEM ANALYSIS OF CONVERTING NON-RECYCLABLE PLASTIC WASTE INTO VALUE-ADDED PRODUCTS IN A PAPER INDUSTRY CLUSTER IN INDIA

by
Padmabhushana R. Desam

Submitted to the System Design and Management Program on August 16, 2013
in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Engineering and Management

ABSTRACT

Waste plastic, both industrial and municipal sources, is posing a major environmental challenges in developing countries such as India due to improper disposal methods. Large quantities of non-recyclable plastic waste get collected in paper recycling plants in Muzaffarnagar and other regions in India. The plastic waste is typically in the form of protective covers, thin film, binding coils etc., which gets separated from paper during the pulping process. Because of its low value in recycling markets, the plastic waste is currently being burned as a substitute fuel for biomass in meeting the steam generation needs in paper production. Though incineration of plastic along with other solid waste for energy recovery is a common practice in countries like Europe, low technology employed in grate boilers without proper environmental equipment are creating serious problems in this region due to combustion-generated pollution. Instead, pyrolysis technologies in combination with innovative catalysts are evolving in recent years for converting waste plastic into fuel oil, diesel, and LPG. These technologies are proven to be safe and environmental-friendly, while producing value-added products that are in high demand.

The primary objective of this research study is to investigate suitable technologies to convert waste plastic that is generated in the Muzaffarnagar paper cluster into value-added products, while considering certain unique requirements such as the ability to handle large quantities of mixed plastic, availability of biomass heating sources, lack of skilled workers, and limited capital and operating costs that play an important role in new technology adoption. Moreover, implementation of a suitable technology subject to economic and social considerations in this region is explored at a system-level. This systems thinking approach is deemed to be suitable for handling such complex problems, where non-technical issues play a crucial role in finding an appropriate solution.

Thesis Supervisor: Charles H. Fine
Title: Chrysler Leaders for Global Operations Professor of Management

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

My sincere gratitude goes to Prof. Charlie Fine, both for actively contributing to this work and for providing exceptional guidance on this study. I am very fortunate to work with him because his systems thinking ideology created a platform for me to apply what I was learning in the System Design and Management program at MIT for solving real world complex problems. He gave me the freedom to explore on this topic and always welcomed my ideas. Also, this work wouldn't have been possible without the generous funding through a fellowship program by the newly formed Tata Center for Technology and Design at MIT.

I am indebted to Mr. Pankaj Aggarwal, Managing Director of Bindlas Duplux, for his support in the form of his valuable time, knowledge, and resources. He had opened doors to his facilities and brought many important connections needed to conduct this study. It was a great pleasure to work with him, who in my view is the most dynamic SME owner and entrepreneur in the Muzaffarnagar region. Special thanks to Priyanka Bakaya, founder of PK Clean, for her in-kind contributions in the form of several analytical studies. I would also like to extend my thanks to Elsa Olivetti and Chintan Vaishnav for their guidance.

My wife, Shalini, has been a constant support throughout my graduate studies at MIT and in my life. She took many sacrifices in this endeavor and managed both of our kids, Rohan and Risha, without my help. Words wouldn't do justice to thank her. So, I dedicate this thesis to her as a token of my appreciation for her love and support. I am blessed to have great parents and in-laws, who had encouraged and supported me to reinvent myself with the SDM program at MIT. Particularly, my father-in-law (Dr. S. S. Reddy) has been a source of strength for me through his spiritual and enlightening conversations, above all his affection.

CHAPTER 1

INTRODUCTION

Waste plastic is currently posing major environmental and health issues in developing countries, such as India, due to lack of proper disposal methods or waste management strategies[1]. If the status quo continues, the problem will get worse in the future due to the rampant use of plastic in many applications where metals were traditionally used. In addition, the high economic growth in several Asian countries such as India and China significantly increased the overall use of plastic in daily use, subsequently more waste at the end of the life cycle. The two main sources of plastic waste are industrial and municipal sources. The industrial sources typically consist of process waste and defective products, whereas the municipal sources comprise of plastic disposed from households after use. This thesis primarily focuses on the plastic waste from industrial sources, specifically from the paper recycling industry in an industrial cluster located in India. Though this analysis is primarily concentrated around a paper cluster, the findings and recommendations have wider applicability to mixed plastic waste and can impact several similar paper clusters and other industries in India and in other developing countries.

Muzaffarnagar Paper Industry Cluster

India currently produces 10 million tons of paper and paper board products and mainly imports specialty paper. About 47% of this production uses recycled waste paper as a raw material, 21% agro-based raw materials such as bagasse and wheat straw, and the remaining production comes from wood [2]. The paper production is projected to increase at 7% annually to meet the demand and is expected to reach nearly 22 million tons by 2025.

Figure 1 below provides a summary of the Indian paper industry. In the Indian scenario, small and medium enterprises (SMEs) play an important role in the pulp & paper industry by accounting for 33% of the yearly production. These SMEs, more than 300 in total, have an average production capacity of about or less than 50 tons per day (tpd) and make a variety of paper products primarily from recycling waste paper and agro-based raw materials. Though the SMEs contribute to 1/3rd of the total paper production, they carry nearly 60% of the pollution load in the form of various effluents.

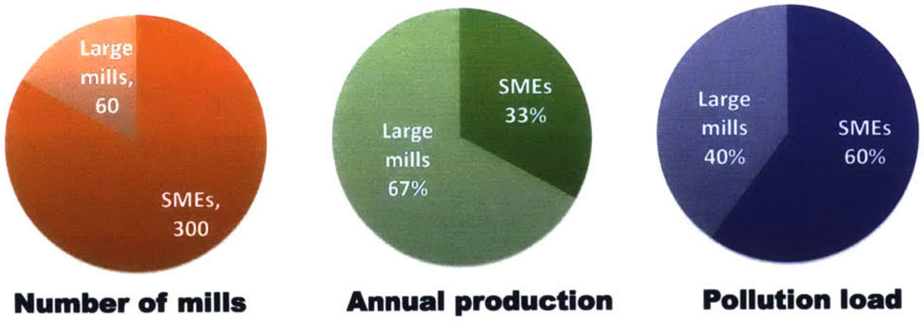


Figure 1 An overview of the Indian paper industry

The major focus of this work is centered on Muzaffarnagar city, which is located in Western Uttar Pradesh, India. It has an industrial ecosystem of paper, sugar, and steel mills due to the availability of various raw materials. There are 29 small and medium-scale pulp & paper mills in this region, mainly clustered around Bhopa Road in the city and Shamli in Muzaffarnagar district (refer to Appendix I), accounting for an annual production of 1.2 million metric tons of paper[3]. The paper mills in Muzaffarnagar are located within a three mile radius, which facilitates easy transportation of materials among mills. This paper cluster is unique in many different aspects, which are (1) raw materials used in paper production (2) management structure (3) technology choices and adoption dynamics and (4) scale of operations.

The two primary raw materials used in this cluster are waste paper and agro-based materials such as bagasse and wheat straw for producing Kraft paper for packaging industry. Some of the mills (12 out of the 29) combine both waste paper and agro materials as pulping sources, whereas the others primarily recycle paper. Though these raw materials are being recycled by the industry to conserve natural resources, the paper mills in this cluster are constantly facing significant pressure from the local community and government, mainly due to environmental related issues and the cluster's proximity to two major sacred rivers in India i.e., Ganga and Yamuna[4].

Most of the mills are owned by close-knit families with a very lean management structure. Each mill has a partnership model, ranging from few to more than half-a-dozen partners. Each of the partners has a share in more than one mill, which brings both advantages and disadvantages in decision-making. Some partners are active and act as managers of the plants, who make major decisions on investments and operations of the mills. There is an additional layer of supervisors between the managers and workers in the mills. The supervisors typically don't have control on decision-making process and simply follow the orders given by the managers. Majority of the workers in the mills are either semi-skilled or unskilled workers that earn daily wages.

The technology employed in these mills can be classified as mature and outdated in some cases, mostly imported from China and other Asian countries. Most of the paper mill owners are risk averse when it comes to new technology adoption, however quickly implements once benefits are validated in other mills. This result in a large lead times for initial adoption and then quick diffusion times. Also, there is a wide disparity in scale of operations, ranging from 5 tpd in a single unit to 250 tpd over multiple units.

Paper Making Process

Paper is made from natural fibrous materials and is recyclable at the end of life. Irrespective of the raw material choice, paper manufacturing process involve three distinct steps i.e., pulping, paper making, and finishing. While pulping can be made in batches, the remaining two steps are continuous. The Muzaffarnagar paper cluster recycles nearly one million tons of waste paper annually for making Kraft and other types of paper. However, the pulp derived from the waste paper needs to be supplemented with long virgin fibers for providing the necessary strength, which is mainly made from locally abundant agro materials. These agro materials include bagasse and wheat straw, primarily sourced from local farmers and jaggery makers. Figure 2 shows the various material inflows and outflows in a typical SME pulp & paper mill in this region.

The pulping process, outlined in Figure 3, depends on the choice of raw materials and is mainly classified as mechanical or chemical pulping. Chemical pulping is applicable to bagasse

Figure 2 Material inflow and outflow from an SME pulp & paper mill

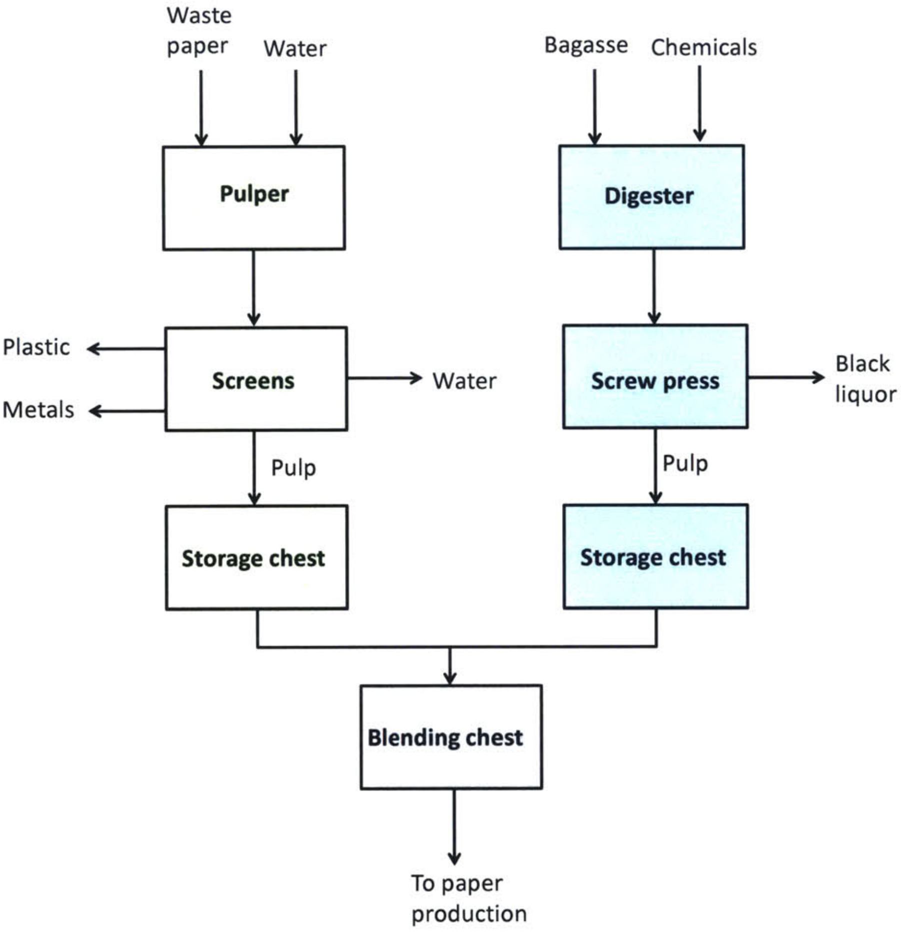


Figure 3 Pulping process in a paper mill that uses recycled paper and agro-based raw materials

and wheat straw feedstock to separate fibres that are bound together with lignin. The raw material is cooked with chemicals at high temperatures in a digester to liberate fibres from the binding material. The pulp from this process is separated through screens, washed, and bleached in some cases. The spent cooking liquor from this process is called black liquor, which is a major source environmental pollution in this region. In mechanical pulping, waste paper (such as cartons, books, newspaper etc., as shown in Figure 4) is mixed with large amounts of water and mechanically stirred in a large mixer. The feedstock usually contains thin layers of plastic attached to it for reinforcement purposes or adhesive tapes on carton boxes, and binding coils on books, which amount to 5-10% by weight. In addition, metals in the form of staple pins are commonly found in this material. The pulp is separated from the mixture using screens and the plastic and metals get separated. Figure 5 shows the waste plastic separated from the pulping process in a paper mill. The resulting pulp is washed and sent to the paper making machinery by mixing with the virgin pulp from the chemical pulping process to meet the requires strength of the final paper product.

Plastic Waste from Paper Production

The total plastic waste from the Muzaffarnagar cluster amounts to more than 200 tpd with nearly 40% surface moisture from the pulping process or nearly about 120-130 tpd on a dry basis. To get a perspective on this amount, Mumbai generates nearly 400 tpd of plastic waste every day, which has a population of more than 12 million[1]. Due to lack of proper disposable methods and government regulation, it is currently being collected and burned by six paper mills in low-efficient grate boilers without proper environmental equipment for recovering

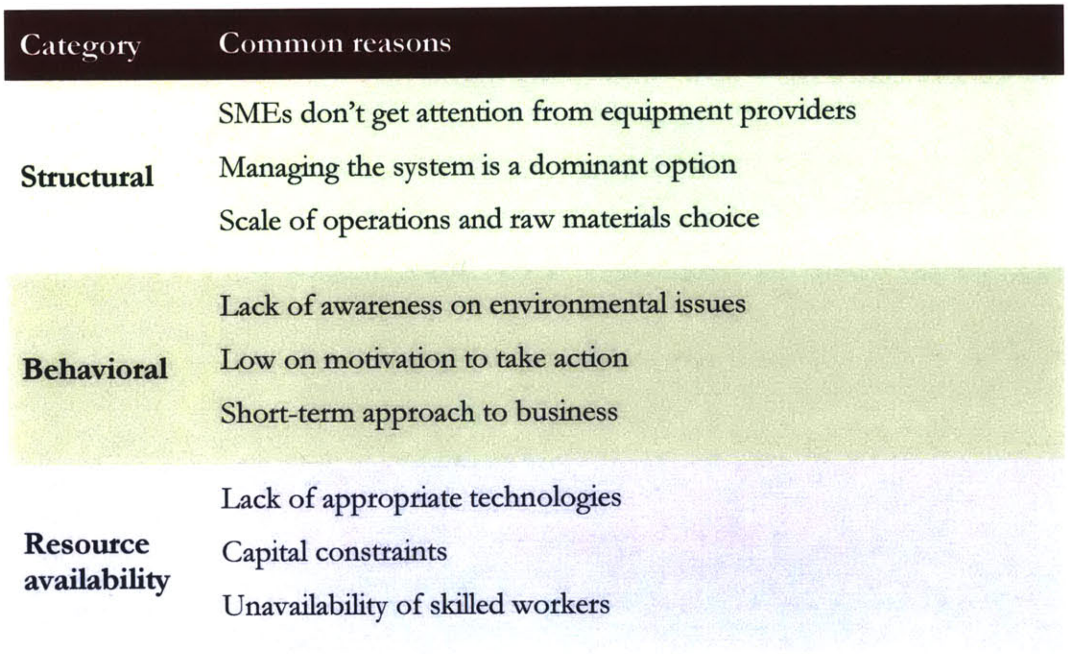
Figure 4 Waste paper feedstock used in paper recycling plants in Muzaffarnagar

Figure 5 Waste plastic separated from the pulping process in a pulp & paper mill

energy in the form of steam, which is then used in the paper making process. Burning plastic inefficiently produces carbon monoxide, sulfur dioxide, toxic emissions such as dioxins and furans (if poly vinyl chloride resins are present in the mix), and fine ash particles during the combustion process. These emissions and fine particulates cause significant air pollution in this region and are detrimental to the health of both workers and city residents. Though alternative fuels such as bagasse and rise husk are abundant in this region, plastic has been burned because it is a waste from their own process and the low-level of technological investment needed for grate-fired boilers. As a result, surplus biomass materials such as bagasse are either being burned in open fields or excessively consumed by jaggery makers in their own processes to get rid of it, which itself creates severe air pollution problems in the form of thick smoke and fine ash particles.

Environmental Pollution from SMEs in the Paper Industry

Some of the most discussed reasons for high amounts of pollution from SMEs in this cluster are issues related to structural, behavioral, and resource availability. Table 1 lists some of the common reasons in those categories, which are predominant in developing countries like India. Most environmental equipment providers target large companies and meet their needs closely than SMEs because of the size of opportunity. Moreover, many pollution control technologies were originally developed by the Western countries for large paper mills, which can't be scaled appropriately to address the unique needs of SMEs in India. For example, solutions like chemical recovery plants to process black liquor may not be suitable for the scale of operations and the raw materials such as bagasse and wheat straw SMEs use. Some of these



Category	Common reasons
Structural	SMEs don't get attention from equipment providers Managing the system is a dominant option Scale of operations and raw materials choice
Behavioral	Lack of awareness on environmental issues Low on motivation to take action Short-term approach to business
Resource availability	Lack of appropriate technologies Capital constraints Unavailability of skilled workers

Table 1 Some commonly known reasons for high amounts of pollution from SMEs in India

structural issues force the paper mill owners to manage the system, which eventually become a dominant option since there aren't many cost-effective solutions available to this particular segment. Similarly, the SMEs are not well aware of the environmental issues and its long-term effects on society. Even if such awareness exists, low motivation and short-term approach to business hinder proper action. In some clusters, SMEs face severe competition from each other and try to expand their businesses to get economics of scale in order to survive. Such environment limits capital allocation for environmental-related investments.

It is interesting to note that only few of the above reasons are related to technology, whereas the others are economic, social, behavioral, and policy related issues. As a result, it is extremely important to consider these non-technical aspects in tandem with technical challenges in finding an appropriate solution.

Thesis Objective

The primary objective of this thesis research is to investigate a system-level solution for addressing the unique challenges faced by SMEs in disposing plastic waste. The system-level solution analyzes and includes important technical, economic, social, and implementation issues in an integrated manner such that the recommended solution is likely to be adopted and creates the necessary impact in reducing the environmental pollution by burning plastic waste. The principal method of research includes interviews with various stakeholders and technology providers, observations from site visits to paper mills and technology demonstration units, and analysis of information for making final recommendations.

CHAPTER 2

PLASCTIC WASTE MANAGEMENT STRATEGY FOR PAPER MILLS

Plastics are synthetic and semi-synthetic organic compounds primarily made from crude oil. The basic units of plastics are monomers, which are shorter carbon-containing compounds. Repeating units of monomers form polymers, synonymously referred as resins, with large chains of heavy weight molecules. Various types of monomers are combined in many different polymers to make an almost infinite variety of plastics with different chemical properties[5]. Table 2 below shows a typical classification of common plastics by resin type and their respective applications. Most plastics are chemically inert and can be easily molded, which makes them suitable for many applications and are considered as one of the greatest innovations of the millennium[6]. Because plastics don't decay naturally, plastic disposal poses a difficult and significant environmental problem. For example, India produces 5.6 million

Plastic type (number)	Plastic type (name)	Common uses
1	PETE	Soft drink bottles, cooking oil bottles, peanut butter jars
2	HDPE	Detergent bottles, milk jugs
3	PVC	Plastic pipes, outdoor furniture, shrink-wrap, liquid detergent containers
4	LDPE	Produce bags, trash can liners, dry-cleaning bags
5	PP	Bottle caps, drinking straws,
6	PS	Plastic tableware, meat trays, take-away food containers, styrofoam cups and plates
7	Other	Plastics other than 1-6

Table 2 Classification of plastics by resin type and common applications

tons of plastic annually, which includes both muncipal and industrial sources, a fourfold increase since 1999[7]. Though some of the waste is being recycled, there are currently no comprehensive waste management systems in place.

Classification of Plastic Waste from Paper Mills

It is crucial to understand and classify plastic waste from the paper mills in Muzaffarnagar before considering proper waste management strategies because the solution often depends on particular type of resins present in the waste. Plastic waste samples from two different paper mills in Muzaffarnagar were collected and dried to remove surface moisture. One set of samples were cleaned with water and another set with IPA (isopropyl alcohol) to remove foreign residue and analyzed using Fourier transform infrared spectroscopy (FTIR) for determining the resin type.

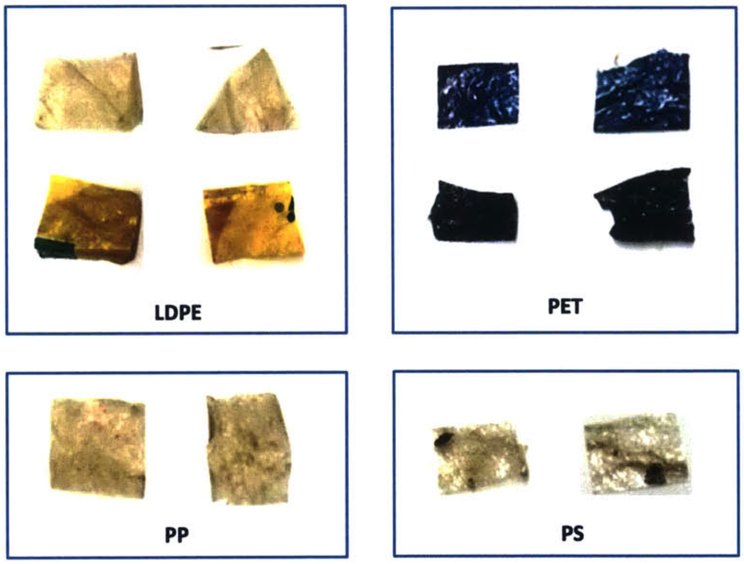


Figure 6 FTIR classification of plastic samples from the paper mills in Muzaffarnagar

Figure 6 shows four different types of resins identified in the analysis, which are LDPE, PET, PP, and PS. In addition, the plastic is in ribbon form and is in small pieces, after being churned by the impeller in the pulping machine. Majority of the plastic waste is composed of PET (45%) and LDPE (40%), as shown in Figure 7. There was only 10% of PS and 5% of PP type resins present in the mix.

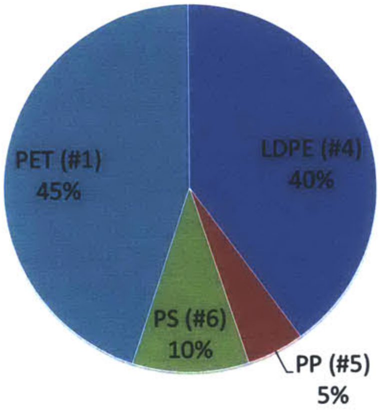


Figure 7 Distribution (%weight) by resin type found in the plastic waste mix

Plastic Waste Management Techniques

There are five different ways of managing large amounts of plastic waste, which is depicted in Figure 8. Landfilling is a common method used in both developing and developed countries. Due to strict environmental regulations, precautions are taken at the landfill sites in developed countries to reduce leaching into underground water resources or emission of harmful gases from landfills. In contrary, these precautions are absent in developing countries and plastic

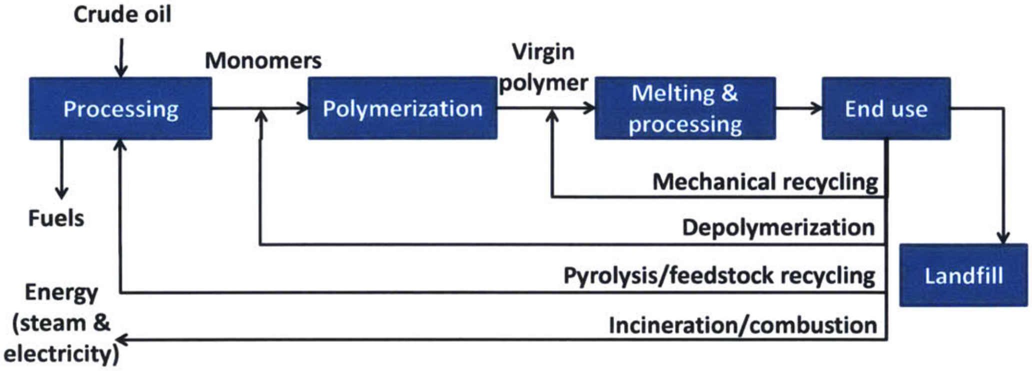


Figure 8 Waste plastic management strategies (adapted from [8])

waste is often visibly found on road side and as large piles in open lands. This practice is becoming unsustainable as the government is facing increased pressure due to unsightliness, leaching into water resources, and other local political issues. In addition, landfilling is also becoming a very expensive option due to rising costs and space availability[7], which also applies to the situation in Muzaffanagar. The paper mills in this cluster are already facing challenges to landfill their other waste streams such as rise husk ash from boilers, which include rising land prices of dumping sites and complaints from local citizens. To conclude, out of the five strategies, landfilling is the most undesirable way of managing plastic waste in this region.

Mechanical recycling has been an economical and the most appealing method for certain type of plastics such as PET bottles[9], which has a good market in India. In this approach, plastic is thoroughly cleaned to eliminate contamination, dried and cut into small pieces. These pieces are then fed into a heated extruder for melting the plastic without altering the chemical structure of polymers. The plastic melt from the extruder is forced into a die arrangement and then quenched and cut into small pellets. These pellets are reprocessed into similar or other applications. However, it is not practical to mechanically recycle plastics that are either contaminated or heterogeneous mixtures[10], which is the case of plastic waste from paper mills. There are several innovations in sorting plastics by resin type such as X-ray fluorescence, infrared, and flotation methods[6]. However, the applicability of these innovations to industrial applications is not economical or practical.

Depolymerization, a third approach, is a process used to recover plastics into a monomer or a mixture of monomers under heat and pressure. Several plastics, such as polymethylmethacrylate (PMMA) and polyethylene terephthalate (PET), certain polyamides, and polyurethanes, are advantageous for such treatment[11]. However, this method is not ideal for polyethylene (LDPE) and polypropylene (PP) type resins[12]. Accordingly, this method is not suitable because nearly half of the plastic waste is composed of these two resins and the difficulties in separating and subsequently handling them with a different method.

When heated in the absence of oxygen, at elevated temperatures, plastic materials go through physical phase change and chemical decomposition to produce hydrocarbon gases and char materials rich in carbon. This process is called pyrolysis, which is commonly found in various applications in the chemical industry[13]. A portion of the hydrocarbon gases can be condensed to form heavy oil, which is typically used in industrial heating applications or can be refined into other fuel products. The pyrolysis process can handle contaminated and mixed waste plastics without additional sorting and is an attractive option for paper mills.

Incineration or combustion of plastic can eliminate waste by recovering energy in the form of heat. The heat from this process can be used to produce either electricity or steam for industrial or similar applications. The most advanced incinerators can be found in Europe for treating MSW, including plastic. The main drivers for European success are strict regulations on the amounts allowed for landfilling and the rising costs of landfilling. However, incinerators need to be fitted with proper environmental equipment to treat the flue gases from combustion[14]. European plants are fitted with some of the best technologies in the world because of stricter regulations on air emissions. Consequently, the pollution equipment alone costs more than half of the total system cost in Europe. Though the waste plastic is currently being burned in Muzaffarnagar for recovering heat, the absence of environmental equipment outweighs the benefits. In addition to pyrolysis, this method can also handle mixed waste plastic as it comes out of the process[15].

Incineration vs Pyrolysis as a Plastic Waste Management Strategy

Out of the five waste management strategies discussed above, incineration and pyrolysis are the only two methods suitable for treating mixed and contaminated plastic waste from paper mills. These two options are compared against each other in different aspects to determine their merit in addressing the unique needs in Muzaffarnagar.

The primary benefit of plastic waste incineration is energy recovery in the form of either steam or electricity. The Muzaffarnagar cluster currently has a generating capacity of 65 MW of electricity from 11 large mills, primarily burning biomass sources such as rise husk and bagasse pith in bubbling fluidized bed (BFB) boilers. High-pressure steam from the boilers is used in electricity production, whereas low-pressure steam is used in the paper making process. In addition, nearly 26 MW of electricity is drawn by 18 small mills from the grid. Though there is a general shortage of electricity in India, these mills are protected by a government policy. If a paper mill is on a grid feeder that has at least 75% of the load from industry, the policy guarantees continuous power supply to support industrial growth. Most of the paper mills in Muzaffarnagar are connected to this uninterrupted grid supply and are not currently affected by shortages.

Incineration for electricity generation in these small mills needs a large capital investment, either for building new plants or upgrading the current grate boilers that make low-quality steam because making electricity needs high-quality steam. Moreover, additional capital investments are needed for environmental equipment to clean up flue gases, which is the major issue with burning plastic. Considering the cost and benefits, there are not strong incentives to produce electricity in the current scenario unless there are going to be significant shortages or electricity price hikes in the future and environmental regulations that are also strictly enforced. In this future scenario, producing electricity either results in maintaining the current profitability when shortages occur or improving the profitability in the case of price hikes, but negative NPV for environmental upgrades. Most paper mill owners react to such changes when they occur than taking a proactive approach unless it results in significant additional sources of income. In essence, a solution that creates additional value favors over a cost reduction opportunity. Some of the paper mill owners in this region were interviewed to validate this argument. It was found that there is not enough motivation or resources even though incineration technology is mature and readily available. However, there is a strong motivation around pyrolysis systems to produce fuel oil from plastic waste because of the high demand in this region. The motivation primarily comes from the fact that it creates an additional source of income to paper mill owners. It was even discovered in a visit to this region that a paper mill owner already started experimenting by setting up a small-scale rudimentary system.

Though it is apparent that the motivations favor pyrolysis systems for economic and behavioral reasons, it is vital to compare these two approaches on energy and environmental aspects in order to find the best approach to manage waste, which is after all the ultimate objective of this research study. Figure 9 shows such a comparison for treating a kilogram of plastic waste using these two approaches. Though pyrolysis systems nearly consume twice the amount of energy compared to incineration, it also captures high amount of energy in the form of fuel products whereas the amount of energy captured in incineration is lower because of stack losses (33% overall efficiency). On a net basis, pyrolysis systems capture 19 MJ versus 7 MJ per kg in case of incineration. As incineration directly burns plastic, it converts all of the carbon into CO_2 and releases approximately 2 kg per kg of plastic. On the other hand, the CO_2 emissions from pyrolysis is associated with only burning small quantities of process gas and

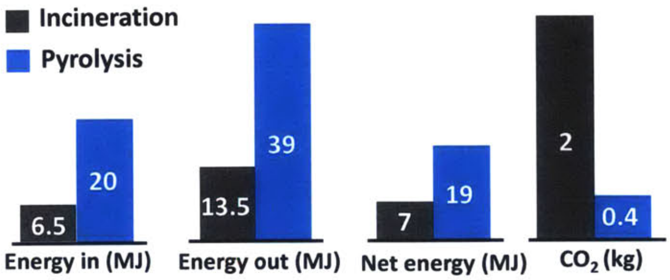


Figure 9 Energy and environmental impact per kilogram of plastic

result in only 0.4 kg. It can be argued that the fuel oil produced from pyrolysis process is eventually burned somewhere else, thus the need to account for the resulting emissions. This argument is not entirely valid when the system boundary is around Muzaffarnagar city and is discussed in more detail in the latter part of the thesis. Wollyny et al., [16] also made similar conclusions as drawn here i.e., incineration of plastic leads to an increase of CO_2 emissions compared to landfill, where as feedstock recycling such as pyrolysis reduces CO_2 emissions and saves energy resources[15].

Based on this analysis, pyrolysis of plastic waste is chosen as a suitable strategy for plastic waste management in Muzaffarnagar. The following section summarizes the approach in selecting a pyrolysis system that meets the requirements of the paper mills in this cluster.

A Systems Thinking Framework for Selecting a Pyrolysis System

A pyrolysis system that simply considers technological needs is unlikely to succeed in Muzaffarnagar because of the previously discussed reasons under the 'Environmental Pollution from SMEs in the Paper Industry' section. Both economics of new technologies and issues related to adoption have to be simultaneously considered in order to find an appropriate system solution, as shown in Figure 10. A framework from Crawley[17] is adopted with few modifications in this thesis research to analyze and include important influences on a system solution, which is shown in Figure 11.

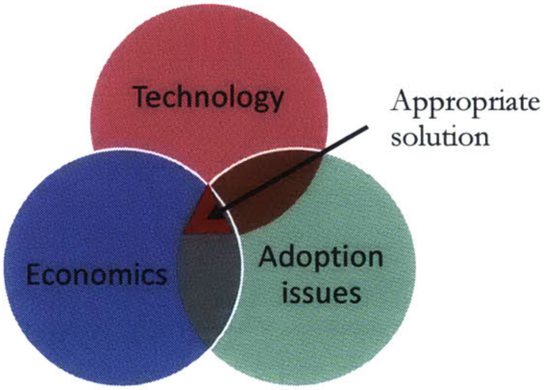


Figure 10 A system solution with important consideration for plastic waste management

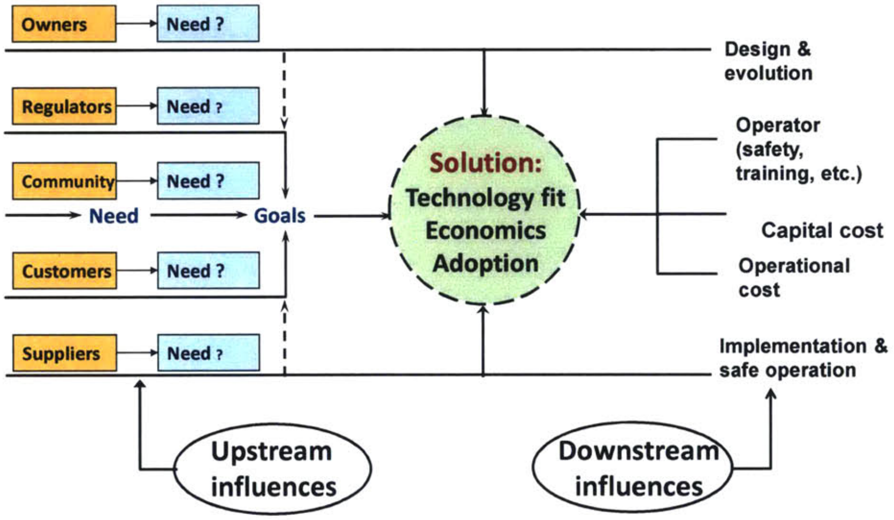


Figure 11 Upstream and downstream influences on a pyrolysis system solution for plastic waste management (adapted from Crawley[17])

The upstream influences on a solution mainly originate from stakeholders, which emphasize the significance of considering needs from important individuals and groups. Table 3 outlines the primary needs of a pyrolysis system in Muzaffarnagar. Some of this information was collected through direct interviews with stakeholders, while others were based on general

Stakeholder	Need
Paper mill owner	▪ Treat large amounts of contaminated and mixed plastic waste from paper mills ▪ Create additional sources of income with a payback period of less than 2 years ▪ Should be able to leverage local heating sources such as biomass from jaggery units and farmers ▪ Technologies that are simple to maintain and operate by semi-skilled workers
Customers	▪ Oil that burns characteristically similar to fuel oil ▪ A local supply free of interruptions ▪ Competitive pricing compared to other fuel sources
Community	▪ Less environmental pollution from waste management ▪ Local employment for workers
Regulators	▪ Protect the environment from waste plastic disposal ▪ Solutions that motivate SMEs to implement and diffuse with less enforcement
Suppliers	▪ Continuous demand for bagasse and other biomass sources ▪ Additional sources of income from biomass and plastic waste

Table 3 Important stakeholders and their needs for a pyrolysis system in Muzaffarnagar

observations and knowledge. Also, it should be noted that not every stakeholder has the same influence on the solution. As a result, some needs receive high-priority which then translates to goals that must be satisfied by the system, whereas the others may or may not be satisfied subject to other constraints. The downstream influences mainly come from capital and operating costs and implementation issues on the solution. Some of these requirements are rigid, whereas others lend flexibility in making the necessary tradeoffs. For example, safety poses a rigid constraint on the solution whereas higher operational costs may be traded with lower capital costs or vice versa. In essence, a system that can satisfactorily balance these upstream and downstream influences is likely to succeed, however require several tradeoffs. The following chapter analyzes pyrolysis technologies in depth and compare them against the systems needs defined above. Chapter 4 examines the economics and implementation issues related to adoption of pyrolysis systems in Muzaffarnagar.

CHAPTER 3

PYROLYSIS AS A TECHNOLOGICAL SOLUTION

To avoid the environmental issues with burning plastic in grate boilers, one of the most attractive options for treating mixed waste plastic in Muzaffarnagar is converting it to fuel oil as discussed in the previous section, which is classified as a feedstock recycling process[18]. When heated in the absence of oxygen, at elevated temperatures in the range of 400-800 °C [19], plastic materials go through physical phase change and chemical decomposition to produce hydrocarbon gases and char materials rich in carbon. This process is called pyrolysis, which is commonly found in various applications in the chemical industry.

Description of a Pyrolysis Process

Pyrolysis processes are mainly classified into two different groups based on whether a catalyst is used in the process or not, which are catalytic and thermal[19]. Table 4 below compares these two processes. Thermal processes typically require higher temperatures and long residence times in the reactors, which consumes high amounts of energy compared to catalytic processes. In general, the energy consumption is typically lower when catalysts are used because of increased surface area for reactions and lower activation energy requirements. However, plastics pose certain specific problems for catalytic cracking, because of high viscosity, which create mass-transfer constraints. Poisoning of catalysts is another major issue especially when treating contaminated plastic waste. Thermal processes are more tolerable to a wide range of resins in the feedstock as opposed to catalysts which are optimized for a range of input resins. Product outputs from thermal processes are broad in composition and subsequently lower oil yields, whereas catalytic processes have better selectivity and higher oil yields[20]. The primary output from thermal processes is typically in the form of heavy oil and is more suitable for industrial applications or needs further refinement for other applications. Advances in catalysts made it possible to directly use the output in transportation applications and yield high-quality fuels[21].

Thermal	Catalytic
High temperature and long residence times (high energy)	Low temperature and low residence times (low energy)
Broad compositional range for output	Greater control over product output
Low yield	High yield
Yields low-octane liquid products and a gas product	Yields high-quality transportation fuels

Table 4 Comparison between thermal and catalytic pyrolysis processes

Figure 12 below illustrates a typical pyrolysis process for oil production. Waste plastic is cut into small pieces and dried before feeding into a pyrolysis reactor since most systems cannot handle more than 10% moisture in the feedstock. Often, the feedstock is mixed with a catalyst for the above mentioned reasons and is fed into the reactor. Another major classification of pyrolysis systems is based on whether the feed is continuous or in batches. In continuous systems, feedstock is typically preheated in the feeder such that it becomes thick slurry which is then fed into the reactor. In contrary, feedstock in its original form is directly fed into the

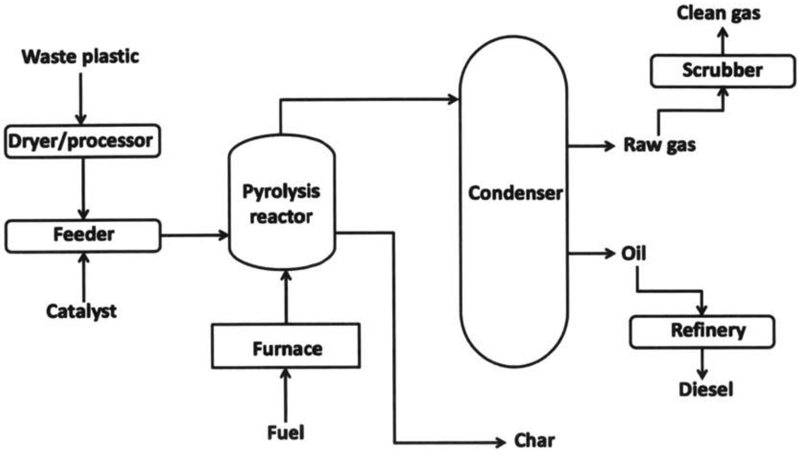


Figure 12 Process diagram of a typical pyrolysis process

reactor in batch processes. The reaction chamber is completely sealed to create an oxygen-free atmosphere and incorporates a mixing mechanism based on the reactor design. The mixing mechanism creates an additional taxonomy for pyrolysis systems in the form of reactor design, which is of rotary kiln, fluidized bed, and stirred tank type[13]. In rotary kiln type, the reaction chamber rotates horizontally at a slow speed for enhanced mixing and uniform heat transfer within a sealed jacket that circulates hot flue gases or heated air. In fluidized bed reactors, an inert mixing medium such as sand and plastic are mixed using the momentum of gas such as nitrogen for enhanced mixing. This type of reactor is highly effective in achieving uniform heat transfer and mixing, however complex to build and operate. Fixed bed or stirred tank reactors have mechanical agitators in the form of impellers driven by electric motors for mixing plastic, however not very effective because of the high viscosity and low thermal conductivity of molten plastic.

Heat required in the pyrolysis process is typically provided by a furnace that either burns solid or gaseous fuels, supplemented by the gases from the process itself. The plastic gets melted and evaporated into gases due to the high temperatures in the reactor. These hydrocarbon gases pass through a series of water-cooled condensers and form heavy oil with different densities. The gases that can't be condensed are scrubbed and then either flared or redirected to the process itself as a source of energy. The fuel oil can then be refined to make diesel or gasoline products using additional processing or can be burned to extract energy for process heating in industrial furnaces. The slag from the process, in powder form, often contains high amounts of carbon and can be burned to recover energy or landfilled based on the local demand situation.

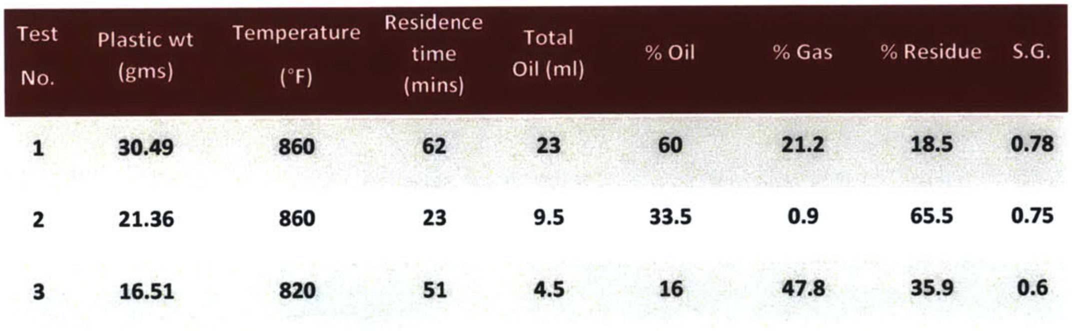
Process Conditions and its Influence on Product Yield

Oil yield from the pyrolysis process strongly depends on the plastic resin type and various process variables such as temperature, heating rate, and residence time in the reactor. Table 5 below summarizes the oil yields for different plastics under typical process conditions. Both PET and PVC type of feedstock are not ideal for pyrolysis because of low yield. PET typically has a good value in the recycling markets provided it is not contaminated and can be separated easily. Further, PVC resins pose some challenges because of the presence of chlorine elements. As mentioned in the previous section, PVC compounds are not present in the waste plastic from paper mills. When PVC is present, the chlorine converts to hydrochloric acid during the pyrolysis process, which needs to be scrubbed. HDPE and LDPE, PP, and PS yield the most and are ideal for pyrolysis process. From this data, it can be concluded that plastic resin type has a first order effect on yields.

Plastic type (number)	Plastic type (name)	Yield (% wt)
1	PETE	10-30 %
2	HDPE	70-80 %
3	PVC	30 %
4	LDPE	70-80 %
5	PP	60-70 %
6	PS	90 %
7	Other	Varies

Table 5 Oil yield from the pyrolysis process for different types of plastics

Process variables such as temperature and residence time play a crucial role on oil yield. Table 6 below summarizes the effect of reactor temperature and residence time on the composition of output products and oil yield on three test samples of plastic waste from Muzaffarnagar. The test samples were heated at a constant temperature of either 860 °F or 820 °F over a range of residence times in a lab reactor and the products were collected for analysis (refer to Appendix II for details). The resulting oil output was centrifuged to separate waxes, which were reported as residue along with remaining solids. Comparing tests 1 and 2, for a constant temperature of 860 °F, there was a decrease in oil yield from 60% to 34% when the residence time was shortened from 62 mins to 23 mins. The higher residue content of 66% under these conditions indicates that pyrolysis was incomplete due to the shorter residence time. When the temperature was lowered by 40 °F in test 3, for similar residence times, the oil yield was significantly lower i.e., only 16%. Combining these two observations, it can be concluded that the yield and composition are more sensitive to temperature than residence time. Similarly, heating rate also effects the composition and yield. Lower heating rates typically result in a product mix of oil, char, and gas. As the heating rate increases, the oil yield goes down with a subsequent increase in gas content. The other two variables that can affect the process are reactor pressure and mixing.



Test No.	Plastic wt (gms)	Temperature (°F)	Residence time (mins)	Total Oil (ml)	% Oil	% Gas	% Residue	S.G.
1	**30.49**	**860**	**62**	**23**	**60**	**21.2**	**18.5**	**0.78**
2	**21.36**	**860**	**23**	**9.5**	**33.5**	**0.9**	**65.5**	**0.75**
3	**16.51**	**820**	**51**	**4.5**	**16**	**47.8**	**35.9**	**0.6**

Table 6 Effect of reactor temperature and residence time on output composition and yield

A Case Study of Pyrolysis for Treating Mixed Plastic Waste

To determine whether pyrolysis is an appropriate technology to treat large amounts of mixed waste plastic in Muzaffarnagar at a commercial scale, a model plant with relevant data was identified in Japan[13]. The same data was used to evaluate the conditions of Muzaffarnagar. The plant was developed by Toshiba Corporation in Sapporo and has been in operation since 2000. Figure 13 shows the process diagram of the plant, which handles 14,800 tons per annum of plastic in two 20 tpd pyrolysis units that operate continuously. Household mixed plastic waste gets collected every week, sorted, and compacted in bales. The bales are delivered to the plant and pretreated in two lines that operate in a batch mode. The plastic is shredded, dried,

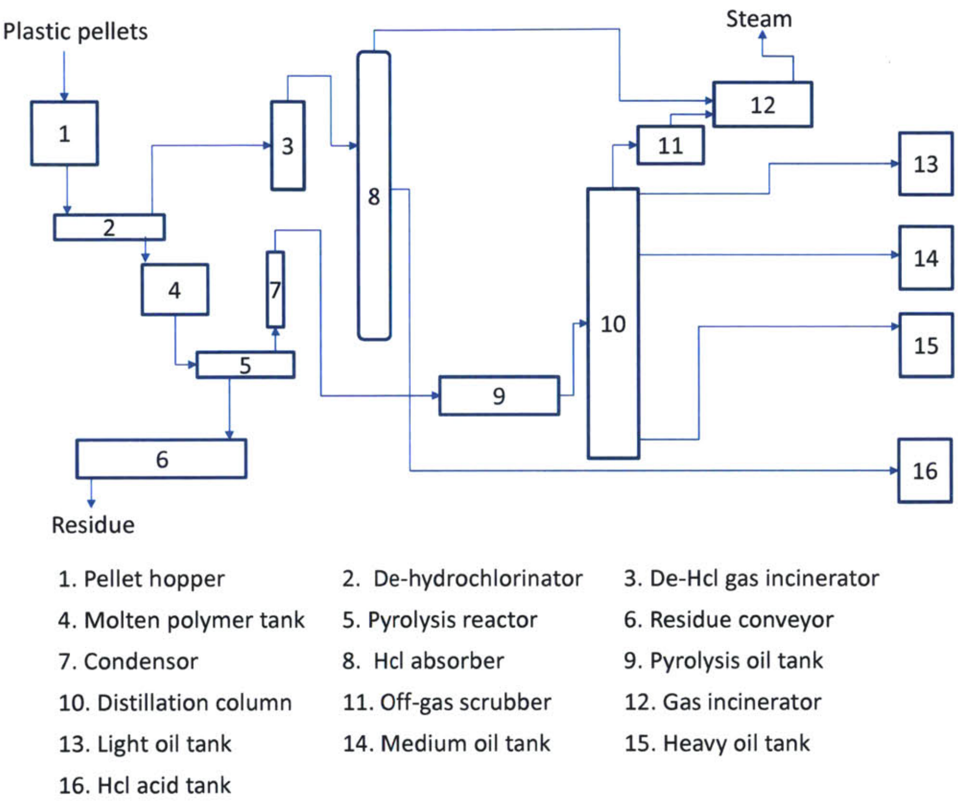


Figure 13 Process diagram of the Sapporo waste plastic pyrolysis plant (adopted from [13])

and pelletized to 6 mm diameter by 20 mm length pellets and stored in a pellet silo. These pellets are then conveyed into a pellet hopper, mixed with calcium hydroxide, and fed into the dehydrochlorinator to remove chlorine from PVC type resins in the feedstock. The pellets get melted at 300-330 °C from the heat supplied in this unit to form molten polymer and gases composed of hydrogen chloride and hydrocarbons. These gases are separated in the molten polymer vessel and sent to the De-Hcl gas incinerator, where hydrocarbon gases are burnt out at 1300 °C. The operating conditions in the incinerator prevent dioxin formation. The exhaust gases are quenched in the HCl absorber and captured as hydrochloric acid. The molten polymer from the vessel is fed into the pyrolysis reactor for thermal degradation. The pyrolysis reactor is a rotary kiln type with hot air jacket maintained at 400 °C and 5 kPa overpressure. Ceramic balls are used to prevent coking problems on the surface of the reactor. The gases rich in hydrocarbons are liquefied into oil in the condenser and stored in the oil drum. The off-gas, mostly comprised of lighter hydrocarbons, goes to waste gas incinerator for energy recovery in the form of steam. The residue, which is a dry and fine powder, is periodically discharged from the bottom of the reactor. The pyrolysis oil is fed into the distillation column with a reboiler and is separated into light, medium, and heavy oil products. Figure 14 shows the composition of waste plastic and product outputs from the plant. More than 70% of the feedstock is comprised of PE, PP and PS type resins, which are ideal for pyrolysis process. Though much of the PET in the form of bottles was separated from the mix before the pyrolysis process, there is still 12% PET in the feedstock that was not ideal for mechanical recycling due to contamination. High amounts of PVC type materials were present from households because of its use in food storage applications, which needed a dechlorination unit. The main product, 57% by weight, from the process is pyrolysis oil, which is the fully condensed oil prior to distillation with a total heating value of 44,750 kJ/kg. A high cetane index of 42 makes this oil suitable for co-generation or process heating applications. Typically, this oil also contains some amount of waxes or other metals, which can be removed by a centrifuge. The residue or char, 16% of the product output, is a dry and fine powder with nearly 47% carbon. This char can be burned in an incinerator or a boiler for energy recovery.

The off-gas, amounts to 18%, mostly consists of C_1-C_4 hydrocarbons and can be easily burned for energy recovery.

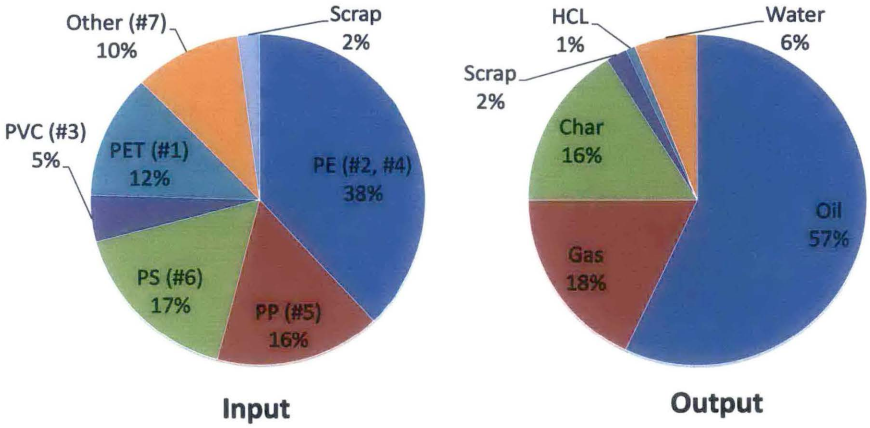


Figure 14 Waste plastic composition and product output composition from the Sapporo plant

The energy balance of pyrolysis systems plays an important role in determining the economic and environmental benefits. Figure 15 (a) shows the energy balance from the Sapporo plant. The total energy input to the plant is 54 MJ per kilogram of plastic, which includes the nearly 34 MJ of energy contained in the waste plastic. The two primary energy inputs to run the plant are electricity and fuel to supply heat to the pyrolysis system. The energy output from the three products amounts to 39 MJ per kg of plastic, which give an efficiency of 73%.

Similarly it is worth evaluating the energy economics of the process, however the results vary widely based on the plant location and markets for the output products. For this reason, the energy economics were evaluated for Muzaffarnagar using assumptions listed in Table 7. Based

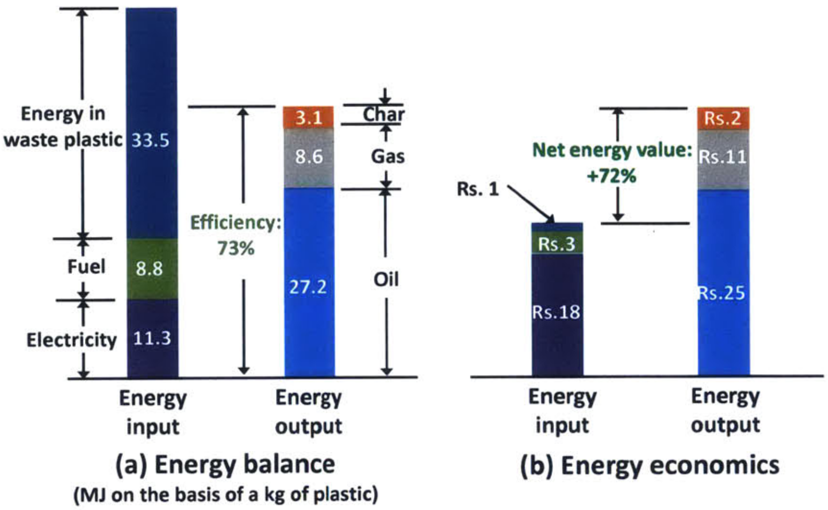


Figure 15 Energy balance from the Sapporo plant operation and economics of a similar system in Muzaffarnagar

S. No.	Assumption
1.	The model plant is Sapporo plant built by Toshiba for treating mixed waste plastic to convert into fuels
2.	1 kg of mixed waste plastic yields 0.57 kg of oil, 0.18 kg of gas, and 0.16 kg of char
3.	The value of 1 ton of waste plastic is Rs. 1,000 in Muzaffarnagar
4.	Cost of 1 kWh of electricity is Rs. 6 for commercial businesses in India
5.	Cost of one ton of bagasse or agro wood is Rs. 3,000 with a heating value (LCV) is 9000 KJ/kg at 40% moisture
6.	Market value of 1 ton of fuel oil is Rs. 40,000-45,000 at a heating value of 42 MJ/kg
7.	Value of char is determined based on the equivalent amount of bagasse fuel on an energy content basis

Table 7 List of assumptions in calculating energy economics of mixed waste pyrolysis system in Muzaffarnagar

on these assumptions, Figure 15 (b) shows the value of energy inputs and outputs, which are valued at Rs. 22 and Rs. 38 respectively per kilogram of plastic. The energy value created by the conversion process is 72%, which should account for capital and operating costs, and profits. These in turn depend on the availability and pricing of commercial systems or development needs. Overall, the value created by the process is encouraging enough to proceed with further analysis.

Commercial Pyrolysis Systems

There are a number of technology providers in various parts of the world, who can supply pyrolysis systems. However, there is no dominant design for pyrolysis systems yet i.e., a standard design that is commonly used by most of the industry, mainly due to its low commercial success that goes beyond technical reasons[22]. The current systems differ mainly in terms of technological complexity, plant capacity, capital and operating costs, type of feedstock it can handle, product output, fuel sources, and the stage in their life cycle. So, the main challenge is to find a system that meets the specific needs in Muzaffarnagar. To find such a system, both interviews and visits were conducted with several system providers in US and China. During these interactions, the capabilities of the systems were investigated and compared against their suitability for treating waste in Muzaffarnagar.

Table 8 below summarizes various technology providers offering commercial-scale pyrolysis systems in North America and Europe. Most of these systems treat waste plastic from municipal sources or from material recycling facilities, except Plastic Advanced Recycling Corporation who claims to have direct experience in treating waste plastic from paper mills.

Company name	Feedstock source	Resin types	Process	Products	Capacity	Investment/ ROI
PK Clean Salt Lake City, UT	Plastic from MSW	2,4,5, and 6 Less than 10% of #1	Pyrolysis with a catalyst	Diesel-grade oil: 70-80% Heavy oil: 20-30%	10 tpd	$1 million
Agilyx Tigard, OR	Post-consumer Post-industrial	1-7 Nylon 6 is not good	Anaerobic thermal reclamation (w/out a catalyst)	Crude oil: 80% Gas: 12% Char: 8%	50 tpd	4 years or less
Climax global energy Allendale, SC	Municipal and private sources	1-7	Microwave pyrolysis (w/out a catalyst)	Crude oil: 75%	3 tpd	3 years
Cynar Plc Central Ireland	Material recycling facilities	2,4,5, and 6	Pyrolysis (w/out a catalyst)	Diesel-grade oil: 70% Diesel-gasoline mix: 25% Char: 5%	10 tpd	£6 million with an EBITDA of £1 million
Envion Washington, D.C.	Scrap plastic from material recycling facilities	2,4,5, 6, and 7	Far infra-red heating	Crude oil: 70% Gas: 15% Char: 15%	8 tpd	3-4 years
JBI Global, Inc. Niagara Falls, Canada	Household waste plastic	2,4, and 5	Low-temperature thermal process with or w/out a catalyst	Diesel-gasoline mix: 87% Gas: 8% Char: 5%	20 tpd	
Plastic Advanced Recycling Corp Chicago, IL	Plastic from paper mills	1-7	Low-temperature pyrolysis with a catalyst	Heavy oil: 50%	30 tpd	$ 5.5 million

Table 8 Technology providers for commercial pyrolysis systems in North America and Europe (Data from interviews and [18])

Majority of the systems can handle resin types 2, 4, 5, and 6 with some limitation on the amount of PET or PVC. The pyrolysis process also differs significantly in terms of catalysts and heating sources. Many processes use thermal energy from combustion gases as a heating source, whereas Envion uses far infer-red waves and Climax global energy uses microwaves as sources of energy. Most of the catalytic processes produce diesel-grade fuels, which demands higher prices in markets. Crude oil or heavy oil seems to be a common output from purely thermal processes. Few of the systems are continuous, whereas the rest of them are either semi-continuous or batch systems. The system capacity also varies significantly, but most of them are within a range of 10-20 tpd. As of now, the two biggest systems with a single reactor are RES Polyflow with a capacity of 60 tpd and Agilyx with a 50 tpd. The payback period is mostly in the range of 3-4 years, with an investment of $1-2 million for a 10 tpd or nearly $10-12 million for a 60 tpd system. Overall, these systems are the most advanced in the world, yet still evolving[23].

Similarly, pyrolysis systems from China were also explored because of their claim to have specific experience in dealing with waste plastic from paper mills. A similar survey on the system capabilities was conducted, however learned that very few differences among systems from three different companies visited during this research. Most of the Chinese systems are rotary kiln type with a capacity of either 8 or 10 tpd and operate in a batch mode, which were primarily derived from rubber tire pyrolysis machines. The loading process takes nearly 4-6 hours and involves manual operation using a hydraulic loading machine that pushes feedstock into the reactor. The heat to the process is supplied using a furnace beneath the reactor, which can burn solid fuels such as wood. There is a metal jacket around the reactor for circulating hot gases, which then pass through a dust collecting system before leaving through the stack. The heating rate is very low and these systems are considered as slow pyrolysis systems, which take about 12-14 hours for the process to complete. Char from the system is removed after cooling the reactor and before loading a new batch of materials. The output from these systems is mainly heavy oil, which has applications in process heating. The Chinese suppliers also offer a separate system for refining the heavy oil further into various products.

In comparing these systems, Chinese manufacturers provide mature and commodity (10 tpd) type systems, whereas North American and European providers offer technologically superior systems that are still evolving. The Chinese systems have enjoyed reasonable commercial success because of the demand for such systems in Asia and Eastern Europe[24]. Though the Western countries have been technology leaders for ling time, historically low oil prices never created favorable conditions for the pyrolysis systems to enjoy high commercial success. For example, only 8% of the plastic waste in the US gets recycled and the rest is landfilled[25]. However, with the recent increase in oil prices and environmental concerns over landfilling or incineration, there is renewed interest in this area and even attracted funding from angel investors and venture capitalists for further technology development. In fact, the systems are currently being scaled up in North America from 10 tpd and beyond for commercial applications. Apart from these external conditions and technology life cycles, significant differences exist between these two types of systems. The Western systems have increased safety and environmental performance built-in, which adds to the price of the system and may be redundant to certain extent in developing countries. It is uncommon to find a system in the West that can use bagasse or wood as a heating source, which is available in abundant quantities in the Muzaffarnagar region. The systems in the West make high-quality transportation grade fuels, which adds technological complexity in reactor design or catalyst since the market for pyrolysis oil is very limited. Whereas, the primary output from the Chinese systems are pyrolysis oil that is used in industrial heating applications in many Asian countries. Many of the Western systems are in a path of development to continuous operation because of the high labor costs and for maximum productivity gains. However, highly automated systems create societal challenges in developing countries like India because of the desperate need to utilize their large workforce that mostly consists of semi-skilled and unskilled labor. This issue is even more predominant in small cities or rural locations because of the unsustainable migration to large cities for labor. Since the technology is still evolving in the Western countries, the providers demand a premium for intellectual property which developing countries cannot afford.

These arguments illuminate how a superior technology might face challenges in developing countries because of economic and social reasons, which further strengthen the need for systems thinking in finding an appropriate solution. The following section evaluates the economics and implementation issues associated with these two types of technologies in depth.

CHAPTER 4

ECONOMICS AND IMPLEMENTATION ISSUES

Economics and implementation issues play a major role in successful adoption of any new technology[26]. Further complexity arises from social and political issues unique to a particular location such as the Muzaffarnagar cluster, which creates additional dynamics in new technology diffusion. Some such dynamics in this cluster are discussed below, which need to be considered while evaluating economic and implementation aspects of the pyrolysis systems.

Technology Adoption Dynamics

The paper mills in this cluster are owned and managed by families and each family member has a share in several paper mills. Typically, major decisions are made by the head of household such as a father or an elder brother in a hierarchical manner in the family. As a result, it has a major implication on the adoption based on whether the primary decision-maker comes across the technology and how he perceives value versus others in the family. In addition, several other dynamics were identified by examining at the past examples of successful adoption of technology in this particular cluster. Most of the paper mill owners are risk-averse, except one who plays a lead user or an early adopter role in technology adoption[27]. The lead user either experiments or sources technologies that either creates additional value or reduces cost of operations from all around the world. At the onset, the new technologies are typically installed in his paper mills and the benefits are demonstrated to other community members, who quickly adopt the technology only if the technology is successful and benefits are attractive. Consequently, the lead user bears most of the commercial risk in this cluster and plays a central role in commercialization. To minimize his risk, the lead user often sources technologies that are either mature or commercially successful elsewhere, but typically shy away from novel and unproven technologies. In addition, the lead user is in a leadership role in the industrial cluster and has significant influence in initiating and implementing new technologies, including environmental-related ones. Thus, technology adoption in this region is not simply based on how superior a technology is and the associated economic benefits.

Other adoption dynamics arise from capital constraints, which is the result of fierce competitive nature of this commodity industry. In order to stay in business, the paper mills continuously expand their production capacity by adding new lines of production which gives them economies of scale with production. As a result, most of the profits are absorbed into plant capacity expansion rather than investing in new technologies. Though economics of new technologies are favorable, those that require large investments may not succeed unless new business models are also invented.

Economics of Pyrolysis Systems

The economics of the pyrolysis system strongly depends on the oil yield through revenue generation, which itself depends on the plastic resin type and process conditions such as temperature range, heating rate, and residence time in the reactor. In addition, the system prices (initial capital) vary widely among the technology providers based on several factors such as intellectual property, technology maturity, and the value of the product output. To quantify the economics of pyrolysis systems, an economic model was built using the assumptions shown in Table 9.

S. No.	Parameter	Value
1.	Plant capacity	60 tons per day
2.	Capital cost	\$1-\$12 million dollars (US \$ = Rs. 59)
3.	Operating & maintenance expenses	Rs. 1,00,000 per ton per annum
4.	Labor	Rs. 65,00,000 per annum
5.	Cost of plastic	Rs. 1,000 per ton
6.	Cost of electricity	Rs. 7 per kWh
7.	Electricity consumption	20 kWh per ton
8.	Cost of fuel (bagasse or agro wood)	Rs. 3,000 per ton
9.	Fuel consumption	175 kgs per ton of plastic
10.	Price of fuel oil	Rs. 40,000 per ton
11.	Capacity factor	0.8
12.	Discount factor	14%

Table 9 Model parameters and values used in the economic model for pyrolysis systems in Muzaffarnagar

Figure 16 shows the sensitivity of oil yield from the pyrolysis process on the payback period on investment, which is assumed to be \$7 million in this case. The payback periods are calculated based on earnings before interest, taxes, depreciation, and amortization (EBITDA) for several reasons. One such reason is that depreciation and tax schedules for SMEs are quite complex. For example, there are no taxes on revenues if the fuel oil is consumed within one of their paper mills or other associated businesses. Moreover, EBITDA is a good metric to evaluate

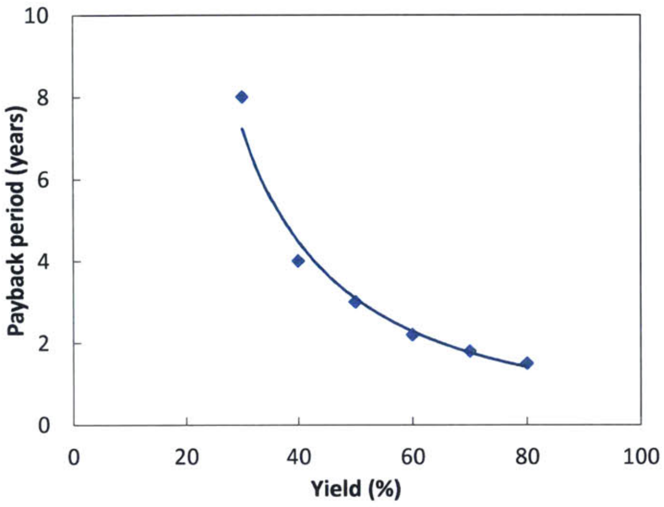


Figure 16 Sensitivity of oil yield from the pyrolysis process on payback period for the investment

profitability when large capital investments are involved. It can be noticed that the payback periods are more sensitive to lower yields than higher yields. For example, the payback period increased from 4 years to 8 years when the yield went down from 40% to 30%. However, for a similar decrease from 50% to 40%, the payback period only went up from 3 years to 4 years. This behavior is primarily the result of a high discount factor 14%, which itself is due to high interest rates in India. When the yields are low, it takes more time to pay off because of low revenues. However, the revenues that come in later years of investment are heavily discounted, which do not have much present value. On the other hand, the value of money is high when the revenues come in earlier years, which is the case of higher yields. Based on several data sources with typical process conditions, oil yield from this mix is estimated to be in the range of 35-40%. Therefore, the payback period can be as high as 4-6 years for an investment of $7 million, which is the typical price of an advanced system from the West. These payback periods don't meet the requirements of the paper mill owners in this region, who favors 2 years or less on investment as per Table 3.

Similarly, Figure 17 shows the sensitivity of the amount of capital investment on payback period at three different yields. As the investment increased, as expected, the slope of the payback period curve also increased progressively due to the high discount factor. However, payback periods are extremely sensitive for large investments especially at lower yields (30%) because of the previously explained reasons. As a result, systems that need high investments may not be suitable for this application unless the yield is higher than 40% or above. The economics seem favorable for systems that require small to medium investments, particularly below $2-3 million.

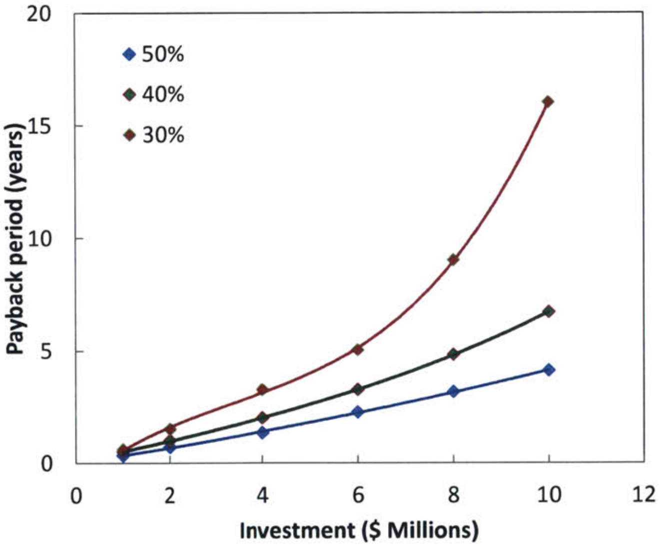


Figure 17 Sensitivity of investment on payback period for various oil yields (60 tpd plant)

Implementation of Pyrolysis Systems in Muzaffarnagar

The economics of pyrolysis systems are attractive in some cases and few systems meet the requirements of investors in this region. The next step is to figure out an implementation plan. Designing and developing a pyrolysis system to meet the unique needs of Muzaffanagar is quite challenging and may not be practical based on the knowledge and resources requires for such a task. On the other hand, owning a plant with advanced technology from the US is not possible either due to the large capital investments ($10-12 million) and other issues in operating technologically complex system in this region because of the semi-skilled workers. Hence, two options were explored for setting up a pyrolysis plant in Muzaffarnagar, which are listed below.

1. Install an advanced system from the US using a profit sharing model
2. Buy a mature system from China for experimentation and improve the system both in terms of productivity and environmental performance

In order to implement an advanced system that pose severe capital constraints for paper mill owners, because of the system price and technological complexity, a business model based on profit sharing was explored. Figure 18 shows the details of the business model. Even though an attractive proposition, most of the US-based technology providers neither have the resources nor expertise to navigate through the complexities of setting up a plant in Muzaffanagar on a profit sharing basis. However, it may be possible to accomplish this through a commercialization partner who can fill the gaps in resources and expertise. Thus, the

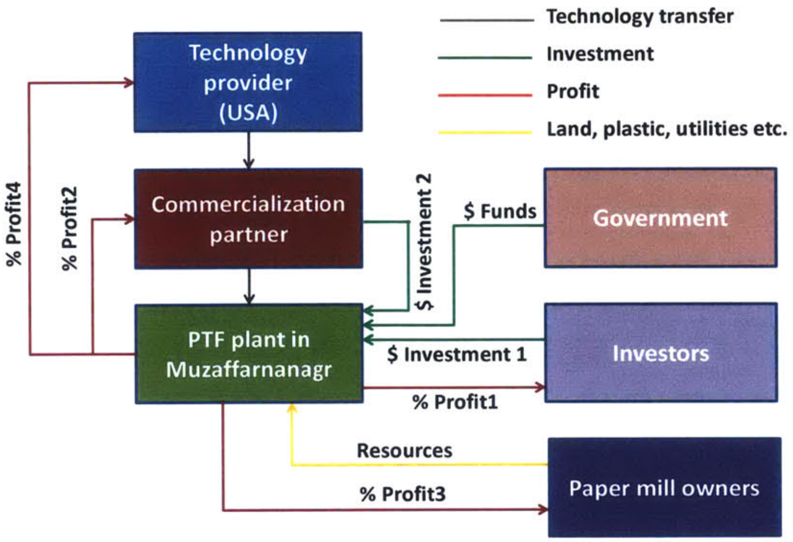


Figure 18 Profit sharing model under consideration for implementing a US technology

commercialization partner in this case brings a part of the investment and expertise for a share in operating profits. Also, the commercial partner has a liability for the success of the project because of the investment. Similarly, the technology provider also receives a share in operating profits, which may be in addition to the initial profit in selling the system for setting up a plant. This may act as an incentive for the technology provider to continuously improve the system and support the project because of the prospects for profit sharing. Other sources of investment include a group of financial investors who passively invests for a return in profit. In addition, government may fund some investment to encourage such waste management projects, which is facing increased pressure due to plastic waste mismanagement. Apart from the technology and capital investments, the plant needs several local resources which play a crucial role in its success. These resources can be supplied by the paper mill owners in the form of land, utilities from their existing resources, and more importantly continuous supply of plastic. In addtion, the paper mill owners can bring their local business networks for selling the output product or consuming it in their own businesses. For providing these resources, they claim a share in profits. In order for this model to be successful, it has to be carefully orchestrated and managed because of the large number of stakeholders and their motivations. The complexity may arise in dividing the profits or value capture in other forms, which determines the success of this approach. This kind of an implementation plan is ideal for setting up a large plant of 50-60 tpd. Two such plants meet the needs of Muzaffarnagar cluster to handle nearly 130 tpd from the paper mills.

The other option is to install mature systems (10 tpd) in a distributed manner and improve the performance such that the systems are optimized for treating mixed plastic waste from Muzaffarnagar. This seems to be an attractive and viable option especially when considering price-performance and small capital investment, which are crucial for successful adoption in this region. Figure 19 qualitatively compares the price and performance of the advanced and mature technologies and their technology life cycles, plotted on an S-curve. The performance here can be a combination of oil yield, safety, and environmental-related aspects from the pyrolysis process. As mentioned previously, the Chinese technologies are mature, hence the performance is already near maximum and major improvements can't be expected. On the other hand, the Western technologies are going through a rapid phase of development and will see drastic improvements in the future as the commercialization progresses. It is even interesting to compare the relative price-performance ratios between these two groups. Because of the large Δprice for a smaller improvement in Δperformance, mature technologies do well on this parameter. However, the required performance in Muzaffarnagar is somewhere in between these two systems and the price favors mature systems. If the mature system is implemented, a plan for improvement is needed in three different areas to close the gaps in performance i.e., safety, environmental performance, and productivity.

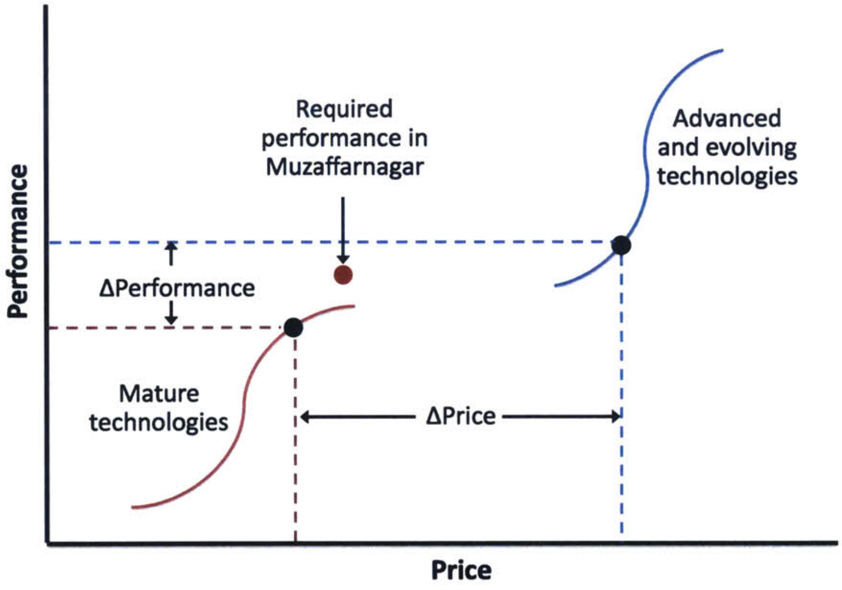


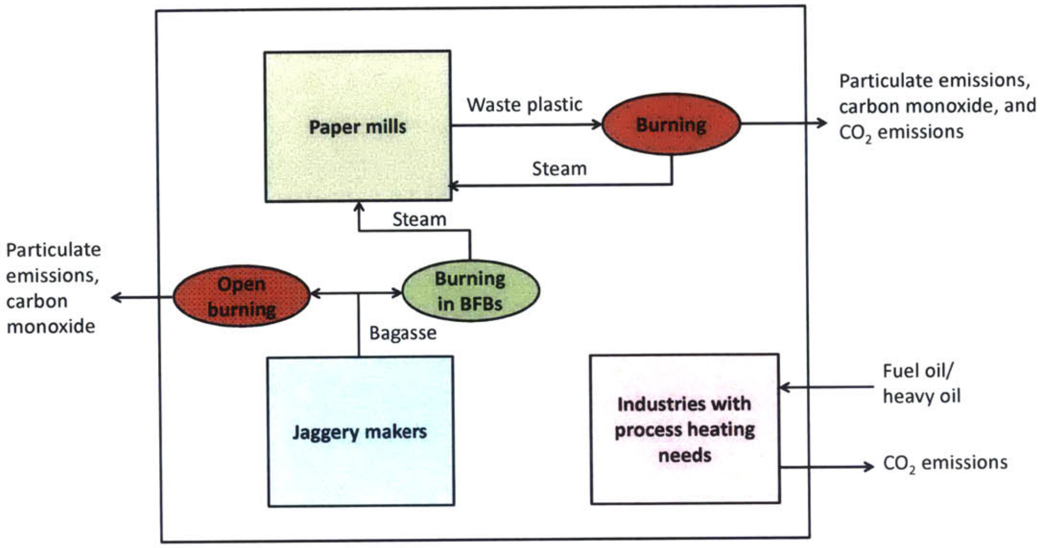
Figure 19 Price and performance comparisons of different technology groups and their life stage.

Irrespective of the source or lifecycle of the technology, safety concerns are inherent in batch processes. In batch pyrolysis process, the reactor needs to cooled such that the left over hydrocarbon gases in the reactor reach a temperature that don't react with oxygen when the reactor door is opened to remove the carbon black and to load a new batch of material. Though there are several layers of safety features embedded in batch systems, it primarily comes to operator training and will remain an issue with human systems due to the unavailability of skilled workers in this region. These problems can be overcome with proper training and advanced temperature sensors and controls as additional layers of protection to the existing systems. Environmental performance can be improved by analyzing and selecting appropriate biomass sources based on ash content, nitrogen and sulfur compounds in flue gases and upgrading current environmental equipment if necessary. Controlling combustion to optimize a right temperature window for the process and determining proper residence time in the reactor for maximum yield and high quality product improves system overall performance. If these improvements can be achieved using the existing resources in Muzaffarnagar, this mature system is more likely to meet the needs and get adopted successfully.

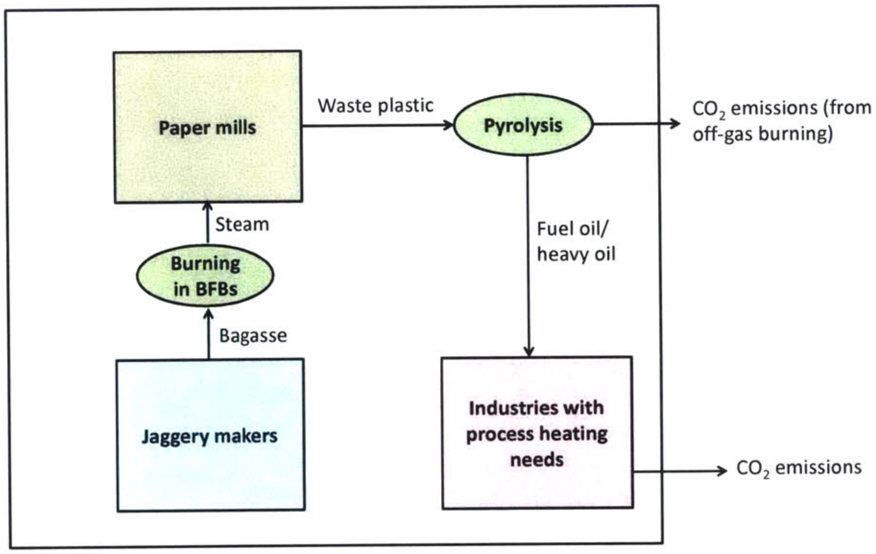
CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

Implementing an appropriate pyrolysis system solution is expected to produce several system-level benefits in the Muzaffarnagar region, while managing the plastic waste from paper mills. Figure 20 (a) summarizes the current emissions scenario from various industries in the ecosystem around Muzaffarnagar. The open burning and excess consumption of bagasse by jaggery makers emit significant amount of particulates and carbon monoxide due to incomplete combustion. On the contrary, bagasse currently being burned by paper mills in the bubbling fluidized bed boilers (BFBs) eliminates such environmental issues. CO_2 emissions from bagasse burning need not be concerned because it is biomass and is a carbon-neutral source. However, burning waste plastic in low-technology grate boilers releases significant amounts of CO_2, particulates, and carbon monoxide emissions. In addition, another major source of CO_2 emissions in this region is industry that consumes fuel oil for process heating needs. This fuel oil is typically purchased from refineries or wholesalers and is transported over long distances in trucks that emit emissions. After implementing the pyrolysis system, the emissions scenario from this region will change significantly, as shown in Figure 20 (b). First of all, the plastic waste can be converted into a high-value product such as fuel oil. The local demand for fuel oil can be satisfied with this recycled resource in place of consuming new earthbound resources. As a net benefit, it has the potential to displace nearly 100,000 tons per



(a) Current scenario



(b) Future scenario

Figure 20 System-level benefits in implementing pyrolysis systems for treating waste plastic in Muzaffarnagar annum of CO_2 emissions. In addition, the carbon emissions in long-distance transportation of traditional resources can be avoided because both the supply and demand are within a five kilometer region. The heating source for pyrolysis process can use the surplus carbon-neutral biomass materials in this region. When burned in the combustion chamber with proper environmental equipment, as opposed to open fires, the air pollution issues from burning solid fuels can be controlled or even avoided altogether. At the same time, this creates a new source of income to jaggery makers and sugarcane formers in the region. Since the plastic can now create high-value products, the paper mill owners are motivated to use the plastic for converting to oil instead of burning in grate boilers. As a result, they will have to find alternative fuels for meeting their own energy needs, which strongly favors biomass materials such as bagasse and rise husk because of their abundant availability and favorable economics. Overall, this solution is going to solve some of the environmental challenges in the region while creating value for several stakeholders in the system. Based on this analysis, pyrolysis is recommended as a suitable strategy to manage plastic waste from the paper mills in Muzaffarnagar.

The future extension of this work can be taken in many directions. In addition to the performance improvements detailed in the previous section, other areas that might add value and worth pursuing are outlined below.

- The plastic waste that comes out of the pulping machine contains nearly 40% of surface moisture whereas most pyrolysis processes can't tolerate more than 10%

moisture. Subsequently, cost-effective methods to bring down the moisture to desired levels have great potential to complement this work.

- The suitability of process gas from pyrolysis for applications such as cooking or other industrial applications
- Biomass gasification at a small-scale to meet both the heating requirements for pyrolysis process and the steam requirements in the paper mills as an entirely different option
- Further investigation of applicability of this system to treat plastic found in municipal solid waste

BIBLIOGRAPHY

[1] D. Mahapatra, "Plastic waste time bomb ticking for India , Supreme Court says," *Times of India*, New Delhi, Apr-2013.

[2] A. K. Dixit, R. K. Jain, and R. M. Mathur, "Innovations & Process Development For Efficient Operation of Chemical Recovery System In Paper Industry," *IPPTA*, vol. 24, no. 4, pp. 119–124, 2012.

[3] Deloitte, "Manual on Energy Conservation Measures in Muzaffarnagar Paper Cluster," 2011.

[4] Central Pollution Control Board, "Charter for Water Recycling and Pollution Prevention in Pulp & Paper Industries in Ganga River Basin.," New Delhi, 2012.

[5] C. Freudenrich, "How Plastics Work," 2007. [Online]. Available: http://science.howstuffworks.com/plastic.htm.

[6] A. K. Panda, R. K. Singh, and D. K. Mishra, "Thermolysis of waste plastics to liquid fuel A suitable method for plastic waste management and manufacture of value added products — A world prospective," vol. 14, pp. 233–248, 2010.

[7] Indian Express, "Not enough landfill sites to dump plastic waste," Apr-2013.

[8] F. Perugini, M. L. Mastellone, and U. Arena, "A life cycle assessment of mechanical and feedstock recycling options for management of plastic packaging wastes," *Environmental Progress*, vol. 24, no. 2, pp. 137–154, Jul. 2005.

[9] G. P. Huffman, "Feasibility Study for a Demonstration Plant for Liquefaction and Coprocessing of Waste Plastics and Tires," *Preprints of Symposia-Division of Fuel Chemistry American Chemical Society*, vol. 42, pp. 1033–1038, 1997.

[10] S. M. Al-Salem, P. Lettieri, and J. Baeyens, "Recycling and recovery routes of plastic solid waste (PSW): a review.," *Waste management (New York, N.Y.)*, vol. 29, no. 10, pp. 2625–43, Oct. 2009.

[11] J. Brandrup, M. Bittner, W. Michaeli, and G. Menges, *Recycling and recovery of plastics*. New York, NY: Hanser, 1996.

[12] J. Shabtai, X. Xiao, and W. Zmierczak, “Depolymerization-liquefaction of Plastics and Rubbers. 1. Polyethylene, Polypropylene and Polybutadine.,” *Energy Fuels*, vol. 11, no. 1, pp. 76–87, 1997.

[13] J. Scheirs and W. Kaminsky, *Feedstock Recycling and Pyrolysis of Waste Plastics: Wiley Series in Polymer Science Series.* John Wiley & Sons, 2006, pp. 0–470.

[14] E. A. Boettner, G. L. Ball, and B. Weiss, “Combustion Products from the Incineration of Plastics,” Ann Arbor, MI, 1973.

[15] S. Peter, “LCA of Management Options for Mixed Waste Plastics,” Banbury, Oxon, 2008.

[16] V. Wollny and P. Weinem, “Comparison of Plastic Packaging Waste Management Options Feedstock Recycling versus Energy Recovery in Germany,” vol. 5, no. 3, pp. 49–63, 2002.

[17] E. Crawley, “System Architecture.” MIT, Cambridge, MA, 2012.

[18] 4R Sustainability Inc, “Conversion technology□ : A complement to plastic recycling,” Portland, OR, 2011.

[19] J. Aguado, D. P. Serrano, and J. M. Escola, “Fuels from Waste Plastics by Thermal and Catalytic Processes: A Review,” *Industrial & Engineering Chemistry Research*, vol. 47, no. 21, pp. 7982–7992, Nov. 2008.

[20] F. Pinto, P. Costa, I. Gulyurtlu, and I. Cabrita, “Pyrolysis of plastic wastes 2 . Effect of catalyst on product yield,” *Journal of Analytical and Applied Pyrolysis*, vol. 51, no. 1–2, pp. 57–71, 1999.

[21] F. Pinto, P. Costa, I. Gulyurtlu, and I. Cabrita, “Pyrolysis of plastic wastes. 1. Effect of plastic waste composition on product yield,” *Journal of Analytical and Applied Pyrolysis*, vol. 51, no. 1–2, pp. 39–55, Jul. 1999.

[22] J. M. Utterback, *Mastering the dynamics of innovation*, Boston, MA: Harvard Business School Press, 1996.

[23] RTI International, “Environmental and Economic Analysis of Emerging Plastics Conversion Technologies,” Research Triangle Park, NC, 2012.

[24] G.-H. Zhang, J.-F. Zhu, and A. Okuwaki, "Prospect and current status of recycling waste plastics and technology for converting them into oil in China," *Resources, Conservation and Recycling*, vol. 50, no. 3, pp. 231–239, May 2007.

[25] EPA, "Plastics Recycling Facts." [Online]. Available: http://www.epa.gov/osw/conserve/materials/plastics.htm.

[26] E. Rogers, *Diffusion of Innovations*, 5th Edition. The Free Press, 2003.

[27] C. Herstatt and E. Hippel, "From Experience: Developing New Product Concepts Via the Lead User Method: A Case Study in a 'Low-Tech' Field," *Journal of Product Innovation Management*, vol. 9, no. 3, pp. 213–221, Sep. 1992.

APPENDIX I

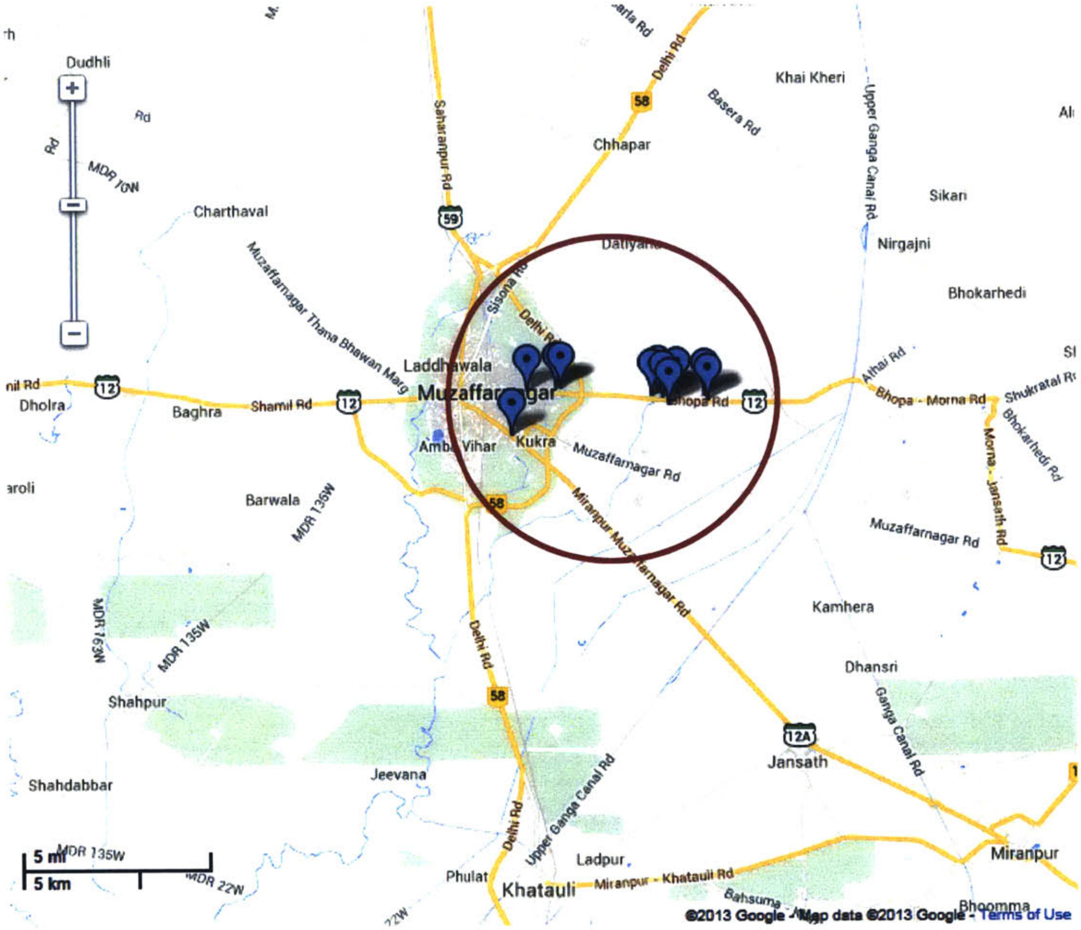


Figure A 1 Location of paper mills in the Muzaffarnagar cluster

APPENDIX II

	Test			
No.	**1**	**2**	**3**	
Plastic	30.49	21.36	16.51	g
Temperature	860	860	820	F
Residence time	62	23	51	mins
Residue	5.65	14	5.92	g
Oil	18.38	7.16	2.7	g
Total Oil	23.5	9.5	4.5	ml
Specific Gravity	0.78	0.75	0.6	g/ml
Gas Yield	21.2%	0.9%	47.8%	%
Coke Yield	18.5%	65.5%	35.9%	%
Oil Sample				

Table A 1 Lab-scale pyrolysis results of plastic waste from Muzaffarnagar (Courtesy of PK Clean, Salt Lake City, UT)

The FTIR analysis shown in chapter 2 and the lab-scale pyrolysis tests with the above data were conducted by PK Clean as an in-kind study. The pyrolysis tests didn't use any of the innovative catalysts PK Clean had developed, instead a simple thermolysis process.