E-waste Management Using Blockchain based Smart Contracts

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***Abstract*--In the world of technology, change is the only constant. As soon as people start adapting to a new invention, another innovation starts paving its way into people's lives. Each change in technology brings in new and improved devices. Old devices are replaced and abandoned. Such Electronic and Electrical Equipments (EEEs) that are discarded by users are termed as e-waste. Management of e-waste includes proper collection, segregation and recycling of discarded devices in an environment friendly manner. The volume of EEEs that is produced throughout the world, has led governments in various countries to create strict policies, to ensure efficient disposal of the generated e-waste. The Indian government also upgraded its E-Waste Management (EWM) laws in 2016 and 2018. These laws are a step towards environment friendly disposal of e-waste but their compliance is still at a nascent stage. Even today, e-waste collection and recycling in India is largely dominated by the unorganized sector, which makes the enforcement of such laws very difficult. In this paper, we propose a novel approach for EWM using blockchain based smart contracts. Blockchain is the technology that enables us to write smart contracts. Smart contracts are self-executing computer codes that take specified actions when certain conditions are met in the real world. EWM using smart contracts will bring in more coordination among producers, importers, retailers and recyclers of EEEs. It will enable the government to regulate e-waste collection and recycling. It will also reduce the imbalance between the organized and unorganized sectors which will lead to increased transparency throughout the process.**

Keywords—E-waste management, Blockchain, Smart Contracts, Ethereum

I. INTRODUCTION

The advancement in science and technology fuels the race between manufacturers of Electrical and Electronic Equipments (EEEs), to launch new devices in the market quickly. Gadgets with improved features and affordable prices encourage users to purchase new products and replace their old devices. These discarded EEEs constitute electronic waste or e-waste. "E-waste refers to EEEs and their parts, which have been discarded by their owners as waste, without the intent of re-use" [11]. It includes all those commodities that have either reached their end-of-life as a product or they do not serve a useful purpose to the user. Any abandoned household or business item, with circuitry or electrical components, with power or battery supply, comprises e-waste. Televisions, air conditioners, refrigerators, fluorescent and mercury containing bulbs, computers, printers, photocopiers, mobile phones, and earphones constitute major volumes of electronic waste. The amount of e-waste generated throughout the world, is increasing at an alarming rate. In 2016, all the countries generated a total of 44.7 Million metric tons (Mt) of such waste. This number is expected to increase to 52.2 Mt by 2021 [11]. India, being one of the fastest growing electronics industries in the world, is among the top contributors of e-waste generated in Asia.

EEEs are made up of multitude of components, some containing toxic substances that have an adverse impact on human health and environment, if not handled properly. Often these hazards arise due to improper recycling and disposal processes used [8]. Hazardous elements present in e-waste include lead, mercury, arsenic, cadmium and flame retardants [4]. E-waste also includes ferrous and non-ferrous metals, plastics, glass, printed circuit boards, rubber and other items [7]. Presence of precious metals like gold, silver and platinum in this category of waste, lures the informal sector to follow unscientific methods of extraction like burning, acid baths etc. Improper disposal of untreated e-waste into landfills leads to penetration of harmful elements in land and water resources. Many developed countries handle their e-waste by illegally exporting it to developing countries, like India, which act as hubs for improper recycling. The uneducated and unskilled labourers involved in segregation and dismantling of waste EEEs also risk their health due to poor practices followed during this process.

E-waste management (EWM) is the process of discarding e-waste in an environmental friendly manner. The first step involves collection of electronic waste items from the consumers, followed by sorting into reusable and non-reusable products. The reusable products are kept for resale while the non reusable products are disassembled. The non reusable dismantled parts go through multiple rounds of shredding and separation. They are either recycled to be used again as new, or they are safely disposed off after proper treatment of hazardous components.

This paper has been divided into six major sections. Following the Introduction, section II describes the related work in the field of EWM, blockchain and smart contracts. Section III gives an overview of EWM rules in India and the basics of blockchain and smart contracts. Section IV contains

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a detailed explanation of the proposed system, followed by section V which describes the experimental study. Section VI presents conclusions and future work.

II. RELATED WORK

The rise in digitization has led to a rise in the amount of e-waste generated throughout the world. This growing trend in the volume of e-waste produced worldwide has been captured by [11]. A detailed review of different kinds of treatments followed for disposing off e-waste in an environment friendly manner has been defined in [7]. It highlights step wise procedure for collection, segregation, disassembly and treatment of electronic waste. India also needs to deal with its domestic e-waste (generated within the country) as well as imported e-waste (dumped into India). An assessment of e-waste management policies and recycling practices within India have been discussed in [4]. In [12] the effects of untreated e-waste on the environment have been highlighted. Major barriers in the implementation of policies for proper disposal of generated electronic waste have been mentioned in [10]. To the best of our knowledge, majority of research in the field of e-waste focuses either on the processing steps involved in EWM or on the harmful effects of improper disposal of EEEs.

The concept of blockchain was introduced by Satoshi Nakamoto in [5]. The working of blockchain along with the details of privacy, anonymity and security, have also been mentioned in [6]. Various applications of blockchain are described in [2]. The details of the working of Ethereum blockchain have been described in [1]. Some research directions for blockchain data management have been mentioned in [3]. As per our knowledge, the approach to handle e-waste using blockchain based smart contracts, has not been proposed in any existing research work. In this paper, we present a novel approach to EWM in India using smart contracts to regularize the process.

III. BACKGROUND

This section aims to provide an overview of EWM policies in India. It also sheds light on the basic concepts behind blockchain and smart contracts.

A. .An overview of E-waste management rules in India

India introduced its first set of EWM laws in 2011, which were improvised in 2016. The first quarter of 2018 saw an amendment to these laws, making them more stringent. The responsibility of collection and channelization of e-waste has been given to the producers, manufacturers, importers, dealers, retailers and refurbishers of EEEs. Authorization to these stakeholders is given only if they meet their phase-wise collection targets of e-waste. Collection targets refer to the amount of e-waste (in number or in weight) that must be collected by the stakeholder, within the specified time duration. The provision of deposit-refund scheme for customers is also made available by the government. To prevent the leakage of e-waste into unorganized sector, the government also directed stakeholders to deposit e-waste only at government authorized collection centers and recycling units, along with proper documents carried by the transporter during this transportation process.

Proper execution of all these rules has been a tough task for the Indian government. Inadequate record keeping by industry participants makes the estimation of the generation of e-waste within India difficult. Due to lack of incentives, consumers tend to give their waste EEEs to rag pickers in exchange of small amounts of money instead of giving back the e-waste to producers/retailers. Only a small quantity (5%) of e-waste reaches formal recyclers, while the remaining (95%) is processed by the informal sector [12]. Many government-authorized collection centers operate at much lower capacity due to the dearth of e-waste entering the formal sector. This causes stakeholders to adopt unfair means to prove their collection targets and safeguard their license to operate. Transporters also act as leakage points of collected e-waste into the unorganized sector. Lack of transparency in the movement of e-waste causes few formal players investing into EWM in India.

B. Blockchain

Blockchain was introduced as the technology behind Bitcoin – the first digital currency to be created in 2009 by an anonymous person/group named Satoshi Nakamoto [5]. The bitcoin blockchain was developed as an alternative to the existing financial system, where banks act as trusted intermediaries for conducting valid transactions and preventing frauds. Banks maintain a private database to store information of their customers, and charge high transaction fees for the services they offer. Satoshi Nakamoto shifted this power, lying in the hands of centralized authorities, to the end-users by designing a decentralized system called blockchain.

Today, blockchain technology lies at the heart of various other cryptocurrencies like Ether, Ripple etc [2]. Transactions on a blockchain include exchange of digital currency. Verified transactions are stored in blocks and these blocks are linked together to form a chain of blocks – the blockchain. A copy of blockchain is present with each node [3]. A node is a device connected to the blockchain network that can initiate and verify transactions. Any device that wants to become a node needs to download a wallet. A wallet is a software that creates a pair of cryptographic keys for the node – a public key and a private key. A node's public key, which is accessible to everyone on the network, acts as its unique identifier for sending and receiving money. When a node wants to send money, it creates a new transaction that includes its own public key, the receiving node's public key and the amount of bitcoins.

Blockchain wallets do not maintain a record of the owner's balance but have access to their copy of blockchain, which stores all transactions that ever happened on the network. So the creator of each new transaction must specify all those transactions which brought him the money that he wants to send. This is done in the transaction's input section as shown in Fig 1.

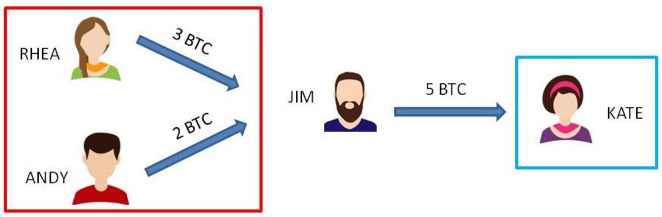

Fig.1. Jim received money (in bitcoins) from Rhea and Andy. He specified these transactions as input when he sent money to Kate.

Before a transaction appears as input, it is called Unspent Transaction Output (UTXO) and later it is referred to as a Spent Transaction. All UTXO specified as inputs within a transaction, must have the same receiver – the node that is creating the new transaction, and the received amounts must add up to atleast the amount that the creator node is trying to send. To preserve the integrity of the newly created transaction, the creator node digitally signs it using its private key, which is hidden from the network.

This transaction is then broadcasted to the neighbouring nodes. When a peer receives a new transaction, it first verifies transaction integrity to ensure that it was actually signed by the creator node and was not tampered on its way. Integrity checks are followed by validity checks which verify that the inputs are UTXO, they were sent to the creator node and the total of all inputs is atleast equal to the amount being transferred by the creator node. Each node uses its copy of the blockchain to track the origin of the specified UTXO. Once validated, the node adds this transaction to its MemPool and relays this transaction to its neighbouring nodes.

These transactions are picked up by Miners and grouped together in a block. Miners are nodes that take the responsibility of appending new blocks to the blockchain. Each block contains a block number, a timestamp, hash of the previous block and a subset of transactions. A block's hash is a unique 64 digit hexadecimal number, generated by feeding the block's contents into SHA256 hashing algorithm. SHA256 converts input of any length and type, into a unique 64 digit hash. This hash changes completely even with a single character modification in the input. Fig.2 displays that the presence of previous block's hash in each subsequent block, links all the blocks together as a blockchain.

Adding a new block requires computing the hash of the new block. This task is made highly difficult by restricting the value of the calculated hash to be lower than a specific threshold value. Since the block contents are static and will always result in the same hash, a variable value called Nonce is included in block contents to find a hash below the target. Miners across the network race against each other to find an appropriate nonce for the next new block. The first one to find a value which makes the hash of the next block below the specified target gets newly created bitcoins as a reward. To fasten the search for nonce, miners use high speed GPUs and ASICs which are designed to perform complex computations fast. This process is called Mining.

Once a miner mines the new block, it is relayed over the network to be confirmed by other nodes and miners. When majority of peers agree on the correctness of the new block (Consensus), it is appended in the blockchain. Modifying the blocks which are a part of the blockchain, requires huge computational power and speed. If a malicious node tries to alter a block, it would change the hash of the altered block and would not match the hash present in next block (in the field: Previous Block Hash). Due to invalid hash in its contents, the next block's hash also becomes invalid. All the subsequent blocks become invalid.

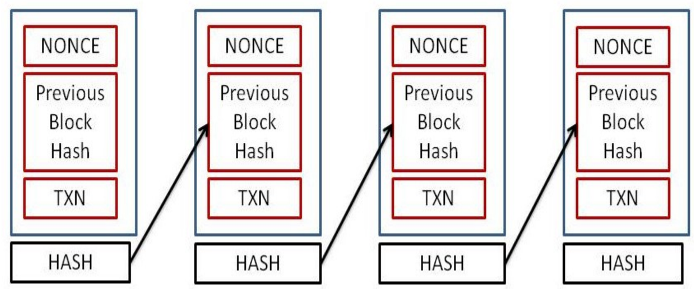

Fig.2. Hash of each block is calculated and included in the contents of the next block. Block number and timestamp have not been shown for simplicity {TXN: set of transactions included in a block}

Hence the attacker must compute new valid hashes of all the blocks following the modified block(s), and this must be done before any new block is further appended to the blockchain. This task is computationally very expensive and can succeed only if majority of the miners contribute their mining power to bring down the network (51% attack). The need to perform complex calculations (known as the proof of work) to create each block, eliminates the need of a centralized authority for establishing trust and preventing fraud. The power of cryptographic keys, hashing and digital signature adds to the security offered by blockchains [6]. The ability of blockchains to offer decentralised and distributed record-keeping with well defined protocols for inter node communication, has made it a popular choice for use in different industries like healthcare, supply chain, real estate etc.

C. Smart Contracts

In 2013, Vitalik Buterin published a white paper proposing Ethereum. Ethereum is a platform that allows its users to create decentralised applications (Dapps) using blockchain technology. Ethereum is not only useful for the execution of normal transactions using the Ether cryptocurrency, but it also facilitates the creation of programs on blockchain using a Turing complete language called Solidity [1]. These codes, which are executed on the ethereum platform, are called Smart

Contracts. Nodes can create and deploy smart contracts on the blockchain to act as an agreement between users. Each node in the ethereum blockchain network maintains the current state of the smart contract and monitors the actions performed by it. Ethereum Virtual Machine executes the smart contract code when required data are provided to it by a node or other smart contract. Smart contracts not only define the rules and penalties of the agreement, just like a normal contract, but also enforce these whenever required. This is done without the need for external enforcement parties.

Using smart contracts, rules can be implemented in an easy and hassle free manner. Any two parties, who decide to abide by a given set of rules, can use these contracts. Ethereum allows such parties to code all the regulations, the penalties and incentives, into a smart contract. If any of these parties do not follow the contract rules, necessary actions, as defined in the code, are undertaken. Hence interacting parties need not trust each other or a third party in case of an agreement based on smart contracts. Proponents of smart contracts have found them to be useful in many diverse fields including insurance, employment, supply chain management and copyrights. We propose to utilize these blockchain based smart contracts in EWM system as explained below.

IV. PROPOSED SYSTEM FOR E-WASTE MANAGEMENT

In this paper, we present a way to improve the situation of EWM in India. Our technique is based on smart contracts, developed using blockchain technology. Bringing government agencies, consumers and stakeholders on the same blockchain platform will lead to improved monitoring and higher transparency in the process. Blockchain will enable proper book-keeping of the EEEs introduced in the market by different producers and retailers. This will enable smart contracts to clearly specify collection targets and penalize the appropriate party whenever required. We also propose the inclusion of customers as members of this blockchain. Providing incentives to customers when they channelize their e-waste to the formal sector, can serve as the first step in reducing the dominance of the unorganized sector in EWM. We have also included collection centers as well as recycling units in our scheme. Smart contracts will help regulate the source and amount of e-waste collected, transported and recycled throughout the process.

The list of stakeholders for the proposed system is shown in Table 1.

TABLE 1: LIST OF STAKEHOLDERS

S.No.	Stakeholder	Description
1	Producer (PR)	A node connected to the Ethereum blockchain, which is either a manufacturer or supplier or importer of EEEs in India
2	Retailer (RT)	A node connected to the Ethereum blockchain, which purchases EEEs from producers and sells them to customers
3	Collection Centre (CC)	Place where PRs temporarily store the e-waste collected from RTs. Owners of CCs are connected to the Ethereum blockchain as nodes
4	Recycling Unit (RU)	Place where e-waste is recycled in an environment friendly way. Owners of RUs are connected to the Ethereum blockchain as nodes

Table 2 shows other types of participants in e-waste management using blockchain.

TABLE 2: OTHER PARTICIPANTS OF E-WASTE MANAGEMENT BLOCKCHAIN

S.No.	Participant	Description
1	Government Agency (GA)	A node on the Ethereum blockchain which acts as a regulator of e-waste on behalf of Indian Government
2	Consumer (CS)	A node on the Ethereum blockchain that uses EEEs for his/her own benefit

The order in which EEEs (new and discarded) are exchanged between these stakeholders and consumers has been illustrated in Figure 3.

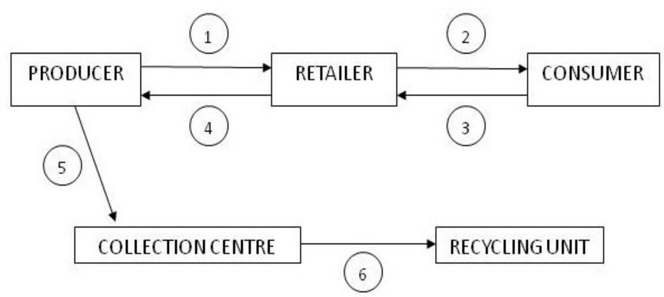

Fig.3. (1) Producer supplies newly manufactured EEEs to the Retailer (2) Retailer sells these EEEs to Consumer (3) Consumer returns their e-waste to Retailer (4) Retailer returns the collected e-waste to Producer (5) Producer delivers collected e-waste to Collection Centre (6) Collection centre transports e-waste to the Recycler for recycling.

In our proposed system, we utilize the Ethereum blockchain to enforce EWM in India. The node representing GAs will be responsible for creating the smart contract for regulating the flow of e-waste across various stakeholders and CSs. GAs will authorize only those PRs and RTs who will join this e-waste management blockchain (EWMB). Owners of CCs and RUs, who wish to establish their businesses in India, must also become a part of this EWMB. CSs will benefit from this system by receiving pre-defined incentives for channelizing their e-waste to proper stakeholders present on the blockchain. Our proposed system can be visualized as shown in Figure 4. The smart contract created by GAs will consist of following modules that will track the activities of each stakeholder/participant.

A. *Authorization Module*

This module of the smart contract will be used exclusively by GAs to provide a digital e-waste license to any PR, RT and owner of CC or RU, allowing them to start their operation in India. This license will state each stakeholder's responsibilities in terms of their e-waste collection targets for upcoming years and the penalty for not meeting the specified target. If the stakeholders fail to meet these targets, the penalty amount, as calculated by the smart contract, will be automatically deducted from the stakeholder's account and transferred to appropriate government account. After a fixed duration, smart contracts will remind the GAs, to either renew or revoke the license of the authorized stakeholders depending on their contribution in e-waste management.

B. *Producer Module*

Each PR must maintain a record of the amount of EEEs that they plan to supply (Supply Amount) in the Indian market. They must also specify the RTs to which they will supply EEEs, the amount of e-waste they have gathered so far, its source and the CCs on the EWMB to which they will supply the gathered e-waste. These records must be provided to the Producer module. This module will call the Collection Module to verify the contribution of e-waste made by PRs. Once verified, Producer module will calculate the remaining amount of e-waste that must be gathered by the PRs to meet their upcoming collection target. If PRs lag behind in their contribution, automated reminders will be sent to them by this module of the smart contract, on behalf of GAs.

This module records each PR's details, so that this information can be cross-verified when the PR interacts with RTs and CCs. It also keeps track of PR's collection target, which can be retrieved by the GAs or the PR itself.

C. *ExchangePR_RT Module*

This module will monitor the exchange of EEEs between PRs and RTs. At the time of purchase, a transaction must be initiated by the RT. This transaction must specify the PR's e-waste license number, the RT's e-waste license number and the record of the units exchanged between them. The module will access this transaction data to verify that each PR's specified Supply Amount (specified in Producer Module) matches the total amount of EEEs that he/she has exchanged with different RTs. In case of a mismatch, the module will reject the transaction and penalize the corresponding PR for his/her malpractice.

D. *Retailer Module*

Each RT must record the amount of EEEs that have been purchased by them (Purchase Amount). This amount will be verified through the ExchangePR_RT Module. RTs must also specify the amount of e-waste they have gathered so far, its source and the PRs on the EWMB from whom they will purchase. The Retailer Module will call the Producer Module to verify the contribution of e-waste made by RTs and whether the PRs specified by RTs match with the list provided by the PRs.

E. *ExchangeRT_CS Module*

This module will monitor the exchange of EEEs between RTs and CSs. It works like ExchangePR_RT Module, but the transaction must be initiated by CS. This transaction will specify RT's e-waste license number, the CS's Aadhar number and the record of the units exchanged between them. RT's Purchase Amount will be verified using Retailer Module by examining all transactions with respect to each RT.

F. *Consumer Module*

CSs who wish to join the EWMB, must call this module to register themselves through their unique identification number like Aadhar.

G. *ReturnCS_RT Module*

CSs invoke this module when they want to return their EEEs that have reached their end-of-life. The details of the discarded EEEs are provided to this module. The ExchangeRT_CS Module is invoked to find the RT to whom this e-waste belongs. An alert is automatically sent to the RT specifying the CS details and the deadline to collect the e-waste. When RT collects the e-waste from the CS, a percentage of the product's original cost is credited to CS account automatically. If the deadline is not met, penalty amount (pre-defined in the module) is debited from the RT's account.

H. *ReturnRT_PR Module*

RTs call this module when they want to return their collected e-waste to the PR from which the discarded EEE was brought. The ExchangePR_RT Module is called to find the PR responsible to collect this e-waste. An alert is sent to the PR with RT details and the deadline. When the PR picks up the e-waste from the RT, Retailer Module is called to update the RT's remaining collection amount. If the PR fails to meet the deadline, penalty amount (pre-defined in the module) is debited from the PR's account.

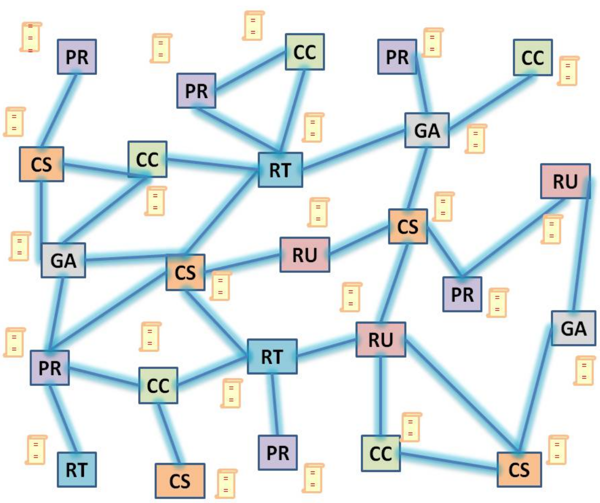

Fig.4. Visualization of the proposed system for e-waste management using smart contracts. The bold blue lines depict peer-to-peer connections between different stakeholders and participants on the e-waste blockchain. The small yellow box close to each node represents the copy of the smart contract running on each node.

I. Collection Module

This module is used by CC owners to authorize themselves on EWMB through GAs. These CCs are provided with a unique e-waste collection license. This license bounds them to accept e-waste as per their collection capacity and deliver it only to authorized RU. CCs must provide a list of PRs from whom they will accept e-waste. The Collection Module verifies this information by invoking the Producer Module. CCs also record the amount of e-waste they have received from various PRs.

J. ExchangePR_CC Module

The PRs will invoke this module when they are ready to transport their collected e-waste to the CC. When CC accepted a certain amount of e-waste, the PR's remaining e-waste value is updated in Producer Module. The Collection Module is also invoked and the information about the amount of e-waste deposited at the CC is updated.

K. ExchangeCC_RU Module

The e-waste collected by CCs is transported to the authorized RUs.

The interactions between the smart contract modules have been illustrated in Figure 5. It also shows how different stakeholders and participants interact on our proposed e-waste management blockchain.

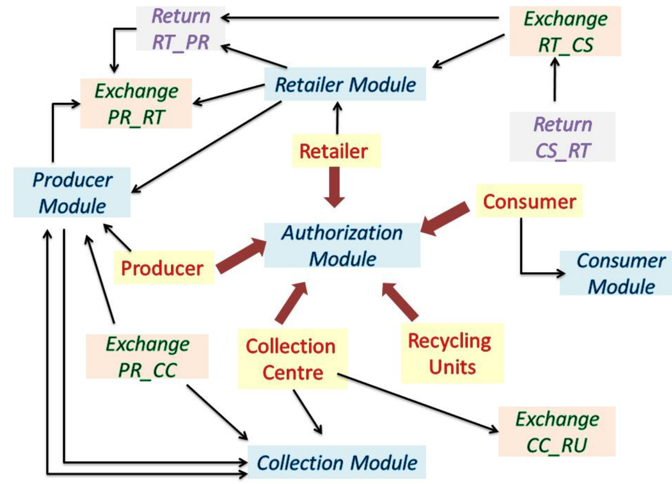

Fig.5 An illustration of the proposed system depicting interactions between different modules of EWM smart contract and the stakeholders of the system.

V. EXPERIMENTAL STUDY

A prototype of the proposed system was developed to test its feasibility. The modules described in section IV were implemented in Solidity using Remix Ethereum IDE. Solidity is a high-level language for implementing smart contracts on the Ethereum Virtual Machine. It was influenced from JavaScript, C++ and Python. Remix is an integrated development environment that allows writing, testing and debugging of Solidity contracts. Remix IDE was connected to Ganache to test the contract modules. Ganache is a tool of the Truffle framework. It provides a personal blockchain to create, deploy and test contracts developed for the Ethereum platform.

VI. CONCLUSION AND FUTURE WORK

In the presented work, smart contracts have been used to regulate the flow of EEEs as well as e-waste through the system. Interactions between stakeholders are monitored by different modules of the smart contract. All modules interact with each other to ensure that at no point any stakeholder indulges in any inappropriate transaction. Details from different stakeholders are obtained so that transactions can be verified using this information. This enables transparency and establishment of trust between interacting parties. The presented system also ensures incentivising and penalising the appropriate parties when the conditions defined in the smart contract are met. A prototype of the presented system was also developed using Solidity and Ganache. This framework can be helpful in enforcing proper implementation of e-waste management laws in India.

This blockchain based e-waste management system can be extended to include parts of EEEs like printer cartridges, toners, mobile batteries, chargers and printed circuit boards used in repairing EEEs. Electronic and electrical parts like these are manufactured and sold in larger quantities than some EEEs and form a significant volume of generated e-waste.

Inclusion of refurbishers will regulate the amount of e-waste that is being reused after technical renovation of the discarded devices. This will result in accurate estimates of the collection targets apart from the e-waste that has been refurbished. When transporters also become a part of this system, we can easily monitor how the collected e-waste is being transported between different parties. Our future work will involve complete implementation of the presented system. We also plan to use IoT devices like smart sensors attached to transport devices that will be used to carry e-waste. This is important to prevent any leakage of e-waste into the informal sector. Development of smart barcodes for EEEs and their parts is also included in our future vision. These barcodes when scanned using decentralized application, will provide the details of stakeholders through which the EEE has reached the consumer.

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