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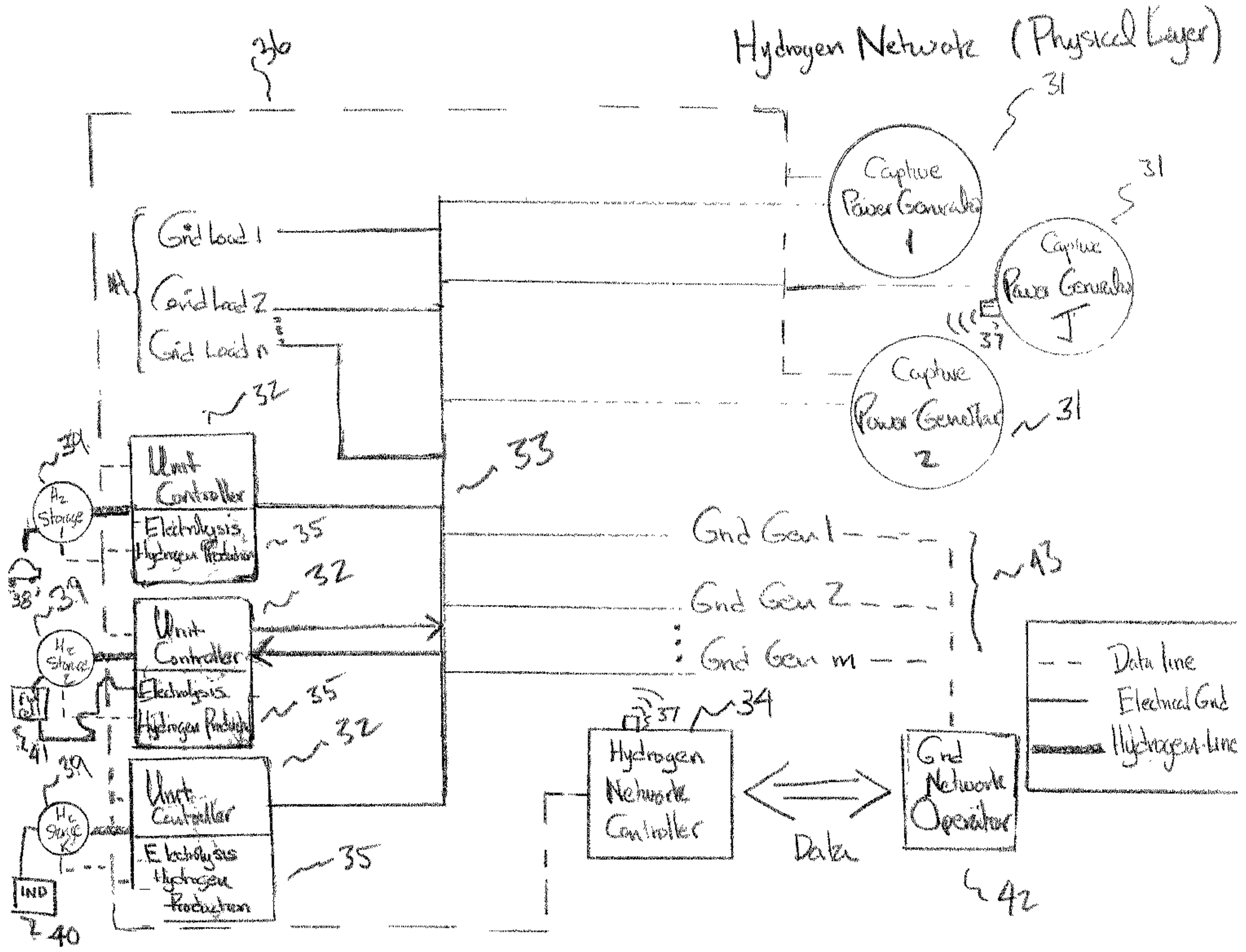
(71) **Demandeur/Applicant:**
STUART ENERGY SYSTEMS CORPORATION, CA

(72) **Inventeur/Inventor:**
FAIRLIE, MATTHEW, CA

(74) **Agent:** TORYS LLP

(54) **Titre :** SYSTEME DE COMMANDE DE RESEAU A HYDROGENE
(54) **Title:** SYSTEM FOR CONTROLLING HYDROGEN NETWORK



(57) **Abrégé/Abstract:**

An energy supply system for supplying hydrogen and electricity in an optimal manner wherein hydrogen is produced for consumers from a network of one or more distributed hydrogen supply systems connected directly to hydrogen production processes using water electrolysis which draws electrical power from one or more captive electricity sources where all resources are connected and have market access to a public electricity grid serving a variety of other electricity consumers and power generators.

ABSTRACT OF THE DISCLOSURE

An energy supply system for supplying hydrogen and electricity in an optimal manner wherein hydrogen is produced for consumers from a network of one or more distributed hydrogen supply systems connected directly to hydrogen production processes using water electrolysis which draws electrical power from one or more captive electricity sources where all resources are connected and have market access to a public electricity grid serving a variety of other electricity consumers and power generators.

Title: System For Controlling Hydrogen Network

FIELD OF THE INVENTION

[0001] The present is directed to systems for controlling energy networks and in particular to systems for controlling hydrogen networks.

BACKGROUND OF THE INVENTION

[0002] Hydrogen can be used as a chemical feed-stock and processing gas, or as an energy carrier for fueling vehicles or other energy applications. Hydrogen is most commonly produced from conversion of natural gas by steam methane reforming or by electrolysis of water. Comparing hydrogen as an energy carrier with hydrocarbon fuels, hydrogen is unique in dealing with emissions and most notably greenhouse gas emissions because hydrogen energy conversion has potentially no emissions other than water vapour.

[0003] However emissions that have global impact, such as CO_2, need to be measured over the entire energy cycle, which must include not only the hydrogen energy conversion process but also the process that produces the hydrogen. Looking at the main hydrogen production means, steam methane reforming generates significant quantities of CO_2 and, unless the emissions are captured and sequestered which is only practical in systems that are very large and where facilities to capture and sequester the gas are available, these gases are released to the environment. In the case of electrolysis, since the electrolysis process produces no environmental emissions per se and transmission of electricity results in little or no emissions, if the electricity is sourced from clean forms of power generation such as nuclear, wind or hydro, hydrogen production by electrolysis generates hydrogen with near zero emissions over the full energy cycle.

[0004] One of the most frequently cited impediments to the development of gaseous hydrogen vehicles is the lack of a fuel supply infrastructure. Because of the relatively low volume density of gaseous hydrogen it is not cost effective to handle gaseous hydrogen in the same way as liquid fuels using central production at a refinery and transporting fuel in fuel tankers. Also. unlike natural gas which is delivered to the customer through a pipeline, there is no large-scale pipeline delivery infrastructure for hydrogen. Analysis of the problem has shown that in the near term, because of the relatively low number of vehicles and hence low market demand in any specific location, the initial infrastructure could build on the existing energy distribution systems, which deliver natural gas and electricity, using on-site hydrogen production processes to convert these energy streams to hydrogen. Using on-site production systems, a widely distributed network of fuel supply outlets, which are sized to meet relatively small demand on a geographical density basis, can be created. The proposed solution of using distributed on-site fuel production systems addresses the needs of a nascent hydrogen fuel market where it may take decades for the fleet of vehicles to be fully converted to hydrogen.

[0005] A hydrogen distribution system having a multiple number of fueling stations connected to one or more energy source(s) in a hydrogen network is disclosed in published Canadian patent application 2,271,448 (Fairlie et al) which is fully incorporated herein by reference. The fuel stations on the network act independently to supply local needs of hydrogen users but are controlled as a network to achieve collective objectives with respect to their operation, production schedule and interface to primary energy sources. A hydrogen network as a collective can be optimized to meet a variety of environmental and economic objectives.

[0006] Because the electrolysis process can be operated intermittently and can be modulated over a wide range of outputs, an electrolyser fuel station can be operated as a “responsive load” on the grid. It is also recognized that for hydrogen networks based on electrolysis, because hydrogen can be stored, for example as a compressed gas in a tank, a hydrogen network can become a secondary market for electricity providing "virtual electricity storage" or demand shifting, by decoupling the electrical energy demand for hydrogen production from when the hydrogen is used. The fueling stations in the hydrogen network can also incorporate hydrogen powered electricity generators such as fuel cells or hydrogen combustion systems which can use hydrogen made by the hydrogen network to re-generate electricity and/or thermal energy thereby acting as emergency power generating systems or as peak shaving electricity generators to reduce costs or emissions during peak demand periods.

[0007] Because the environmental benefits of hydrogen should be evaluated over the full fuel cycle, it is important to the value proposition of hydrogen fuels to be able to measure and control accurately the emissions created in the hydrogen production process. In most electricity market designs electricity is a commodity and it is often difficult to differentiate and assign particular sources of electricity generation to a particular electricity demand. Hence it is difficult to precisely define the emission characteristics of power used in a particular application. For electrolysers connected to the grid in a hydrogen network, the emissions created by hydrogen production are thus often taken to be the average or pool value of the generation mix on line or the marginal rate of emission from increasing power demand when hydrogen is produced.

[0008] At the same time there is recognition that, in the near term, reducing carbon dioxide and other green house gas emissions is the primary objective of hydrogen energy and so the electrolysis solution which offers nearly zero emission production of hydrogen is of particular interest. If the emissions from hydrogen production could be verified, a clean "emission-free" hydrogen could be designated by an "environmental label" and receive emission credits such as fuel tax rebates for avoiding the CO_2 emissions that would otherwise be generated by using other fuels.

[0009] Optimization of energy systems is addressed in the following patents which are each fully incorporated herein by reference: US Patent 5432710 (Ishimaru), US Patent 6512966 (Lof), International Patent Application WO 01/28017 (Routtenberg), □ US Patent 6673479 (McArthur), □ US Patent Application 2003/0009265 (Edwin), US Patent 6021402 (Takriti).

[0010] None of these patents adequately address the need for a system controlling the delivery of energy to a geographically distributed network of hydrogen production units in an optimized way and in a way such that environmental attributes of the hydrogen production process can be audited.

SUMMARY OF THE INVENTION

[0011] The present invention is thus directed in one aspect to a system for ensuring that the energy flow producing hydrogen has a specific emission profile, so that the hydrogen produced by electrolysis has a measurable emission characteristic that can be compared with emissions from other hydrogen production processes such as hydrogen produced by steam methane reforming (SMR). This is preferably achieved by assigning specific energy flows to the hydrogen production systems and auditing the energy flows to ensure that they are used to produce fuel having the desired environmental values.

[0012] By assigning specific generation systems, “captive power producers”, to produce electricity for the hydrogen network there is a significant opportunity to optimize the operation of these systems on a large scale, where energy flows for instance exceed 1 Megawatt, in the context of the public electricity grid and electricity market where energy can be bought and sold into a general electricity market taking advantage that hydrogen can be stored and electricity cannot.

[0013] In this way optimizing the whole energy system encompassing electricity and hydrogen fuel production, an energy utility can be created which serves a two-tier market a prime market where electricity demands are served and a secondary market where hydrogen fuel is produced.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] Figure 1 is a diagram of a hydrogen network in accordance with the present invention;

[0015] Figure 2 is a graph of general electricity demand for a public grid;

[0016] Figure 3 is a graph of output power available from captive power generators;

[0017] Figure 4 is a data flow diagram for a hydrogen network controller in accordance with the present invention;

[0018] Figure 5(a) is a graph of captive power available from a nuclear power plant;

[0019] Figure 5(b) is a graph of hydrogen demand;

[0020] Figure 5 (c) is a graph of a hydrogen production schedule;

[0021] Figure 5 (d) is a graph of captive power sold to a grid;

[0022] Figure 5 (e) is a graph of a hydrogen production schedule for fuelling fleets at night;

[0023] Figure 6 (a) is a diagram of a wind - hydrogen network in accordance with the present invention;

[0024] Figure 6 (b) is a graph of wind power availability profile;

[0025] Figure 6 (c) is a graph of captive power sale to grid;

[0026] Figure 6 (d) is a graph of captive power for hydrogen production;

[0027] Figure 7 (a) is a graph of power supply for hydrogen production including purchase from grid;

[0028] Figure 7 (b) is a graph of emissions for hydrogen production;

[0029] Figure 7(c) is a graph of specific emission rate for grid electricity;

[0030] Figure 8 (a) is a graph of the marginal price of power on public grid;

[0031] Figure 8(b) is a graph of specific emission rate for public grid by time;

[0032] Figure 8(c) is a graph of specific emission rate for public grid by demand;

[0033] Figure 8(d) is a graph of specific emission rate for public grid by demand (including captive power);

[0034] Figure 8(e) is a graph of specific emission rate for public grid by Time (including captive power);

[0035] Figure 9 is a diagram of a hydrogen network in accordance with the present invention;

[0036] Figure 10 is a data flow diagram for a hydrogen network with ancillary services in accordance with the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[0037] The present invention addresses the problem of producing verifiable clean hydrogen fuel from a hydrogen network while at the same time optimizing the operation of such an energy system in an electricity market of multiple users and one or more electricity generators connected by a public electricity grid. The invention contemplates an energy source optimized hydrogen network based on optimizing hydrogen and electricity supply to meet customer needs while controlling fuel production emissions within a pre-defined specification.

[0038] A distributed network of electrolysis systems is a preferred method of hydrogen production as it is potentially the cleanest method of hydrogen delivery. Since the electrolysis process produces no harmful emissions, the by-products are oxygen and water vapour, and since the transmission of electricity to the electrolyser produces no emissions such as produced by trucking tankers of fuel (either directly or indirectly through increased traffic congestion), the harmful emissions generated by the electrolysis process are entirely dependant on the form of primary electricity generation.

[0039] Hydrogen energy systems have been demonstrated such as photo-voltaic (PV) hydrogen vehicle fueling stations (Xerox/Clean Air Now), which operate "off-grid", solely powered by renewable emission-free electricity generation, and hence demonstrate in conjunction with hydrogen fuel cell vehicles a virtually emission free or "zero emission" energy system. However PV power systems are expensive and occupy a lot of space and so other types of clean energy systems need to be considered including wind, hydro-electric, "clean coal" (scrubbed and CO_2 captured and sequestered) and nuclear. These power generation systems are only cost effective on a large scale when operated like a commercial power plant and cannot be scaled down to the size determined to be appropriate for on-site hydrogen production in a hydrogen network (which constitutes a load of typically less than 20 MW per fuel outlet). A cost effective solution is to use the power grid and connect clean energy resources to the electrolysers in the distributed hydrogen network.

[0040] However in many electricity markets clean forms of power generation are not differentiated from other forms of power generation and so clean hydrogen production cannot be demonstrated as the emission rate is taken to be either the average emission rate of all electricity generators producing power on the grid or the marginal emission rate of the generating system operating when electrolysers are connected.

[0041] Furthermore the operating characteristics of the individual power generators, particularly those that produce low emissions, and hydrogen production systems make matching the electricity supply and hydrogen production problematic. Wind energy, although clean, is intermittent, with power produced only when the wind is blowing and so power output is highly variable and unpredictable. Nuclear power on the other hand operates at a fixed output, which also creates problems matching output to variable electricity demands. Hydroelectric power having water reservoirs can be controlled to match demand but is a limited resource, and has great value on electricity networks, used to help ramp up and down electricity supply during periods of peak demand, and is widely used for generator control to control power characteristics such as power frequency and voltage.

[0042] Furthermore the schedule of hydrogen production is dependant on demand which can vary depending on time of day and from day to day, however because of the ability to store hydrogen for example as a compressed gas, hydrogen production can be scheduled at times during the day when energy is available in the cases for example when wind power is generated or at periods of lower electricity demand.

[0043] Because of the sourcing and operating issues cited above the simplest solution is to include captive power generation systems in the hydrogen network and optimize the hydrogen generation as well as electricity production as a system on the grid. The hydrogen network could appear both as an electric supply utility and an electrical load on the grid where the management of the resources within the boundaries of the hydrogen network would be controlled to yield a specified emission characteristic for the hydrogen produced.

[0044] To achieve optimal benefits from such a system a single point hydrogen network controller is provided to schedule and control operation of the different resources connected to the network. The operation of the energy network created by the hydrogen supply systems and captive electrical generators can be optimized by controlling electricity flows either to the electrolysers or to the general electricity market connected to the grid such that the contributions from minimizing the aggregated hydrogen production costs and maximizing the aggregated value of power supplied from captive power producers is maximized, subject to the production constraints of ensuring adequate hydrogen supply at each fuel location and achieving a pre-defined level of environmental emissions for the hydrogen produced. The optimization produces a schedule based on optimizing the following Objective Function over the time horizon control actions can be taken:

$$V(t) : \text{MAX} \{\sum[\textit{Rate of Fuel Production } f^n(t) * \textit{Fuel Value } f^n(t)]_k + \sum[\textit{Available Power from Captive Power Sources } f^n(t) * \textit{Grid Electricity Value } f^n(t)]_j\}$$

k=1……..K electrolysers
j= 1………J captive power generators

Eq.1

[0045] Where defining the functions in the Objective Function, the Rate of Fuel Production is determined by the available energy, from “captive” and grid sources; and the fuel demand at each location on the network. The fuel demand depends on the customer demand forecast over the schedule period and the amount of fuel inventory available in storage at the start of the schedule period.

The fuel demand forecast could be determined by modeling customer demand or through a direct measurement of hydrogen in customer storage systems.

[0046] Knowledge of the specific emission profile from electricity generation is needed so that the fuel production can be labeled according to an environmental impact specification and so if power is purchased from the grid to supplement power from captive sources data is needed from measurement of the average emission rate, or the marginal emission rate or at a rate which is measurable and reasonably assigns emissions given the electricity market design or customer choices on the grid.

[0047] The hydrogen network is preferably controlled by a single point Hydrogen Network Controller which would schedule the operation of the electrolysers on a “day forward” basis or in a schedule period co-incident to the scheduling of the general power grid so that power transactions with grid can be scheduled. During the operating period of the schedule the Hydrogen Network Controller would monitor operation of the different sites and power availability to make supply corrections to balance energy flows as needed.

[0048] Not only can electricity demand for the network collective be tailored to supply but so can the production rate of individual electrolysers and so the Hydrogen Network controller can set a production rate and hence schedule the power consumption of each unit.

[0049] And so the Hydrogen Network controller would determine an optimal hydrogen production schedule based on an electric power demand of the electrolysers, K in number, on the Hydrogen Network:

$$\textit{Total Electric Power Demand of Electrolysers } f^{n}(t) = \sum \textit{[Rate of Fuel Production } f^{n}(t)]_{k} * \textit{[Specific Power Consumption for Hydrogen Production at Station } f^{n}(t)]_{k}. \qquad \textbf{Eq.2}$$

where in the Objective Function (Eq.1):

$$\sum[\textit{Rate of Fuel Production } f^n(t)]_k = \textit{Total Rate of Hydrogen Production } f^n(t)$$

k=1....K electrolysers

Eq.3

which is in balance with power supplied by captive power sources, J in number, and available power from the grid:

$$\textit{Total Electric Power Demand of Electrolysers } f^n(t) = \sum[\textit{Power for Electrolysis from Captive Power Source}_j\ f^n(t)]_j + \textit{Power for Electrolysis from Grid } f^n(t)$$

j=1....J captive power generators
j=1....J captive power generators

Eq.4

such that over the schedule period the following requirements are met, acting as constraints to Rate of Fuel Production and the optimization process:

$$[\textit{Fuel Available in Station } f^n(t+\Delta t)]_k = [\textit{Fuel Inventory } f^n(t)]_k + [\textit{Rate of Fuel Production } f^n(t) - \textit{Rate of Fuel Consumption } f^n(t)]_k * \Delta t \quad \textbf{Eq.5(a)}$$

$$\geq [\textit{Customer Demand for Fuel at Station } f^n(t+\Delta t, \textit{Fuel Selling Price})]_k \quad \textbf{Eq.5(b)}$$

$$\leq [\textit{Maximum Storage Capacity of Station}_k] \quad \textbf{Eq.5(c)}$$

k=1.....K electrolysers (fuel stations)

Eq.5

and the emissions specification as proscribed by the environmental label are met.

[0050] Where in Eq.5(a) Fuel Inventory$_k$ is the measured amount of fuel "on-hand" such as measured by pressure, temperature, volume in compressed storage tanks or such as measured by pressure, temperature, volume, mass of metal hydride in metal hydride hydrogen gas storage, where in Eq.5(b) Customer Demand for Fuel at Station$_k$ being a probabilistic function is set to a defined confidence level of meeting the supply constraint. Rate of Fuel Consumption$_k$ is determined by the Customer Demand for Fuel at Station$_k$

forecast and Rate of Fuel Production$_K$ in Eq 5(a) would be adjusted to satisfy demand constraint at all times over schedule period. The full hydrogen storage condition, Eq.5(c), is a hard limit constraint, however the station would be designed such that at most times it has sufficient storage to meet demand and provide a margin for storage capacity for making real time adjustments to energy flows when the Network has an over supply of power.

[0051] The emission specification could define limits for a number of different emissions including so called criteria pollutants which affect local air quality at the location of the power plant such as nitrous oxides, carbon monoxide, sulphur compounds and hydrocarbon emissions as well as emissions affecting the global environment such as CO_2 and other green house gases. The environmental specification may work on an instantaneous value such as in the case of criteria pollutants where air quality emergency procedures are triggered by achieving certain levels, or emission standards could be proscribed by time average values measured over a specified period of time such, as required for green house gas reporting in some jurisdictions. A key characteristic of the Hydrogen Network is that emissions for the whole fuel cycle including the end use applications such as hydrogen fuel cell vehicles, can be measured and controlled very precisely since they occur only at the power station. Because power plants already have to comply with certain reporting requirements the emission monitoring is often in place.

[0052] Based on specific emission profiles hydrogen production at each location on the network would be scheduled to take advantage of the lowest cost combination of captive power and grid power, which meets hydrogen production and emission requirements. The emission profile is dependant on the emissions of specific generating processes, which must also comply with local emission standards. In the case of captive power generation the emission profile is well defined, reporting directly to the Hydrogen Network Controller and can be monitored. In the case of power purchased from the grid depending on the market design under which the grid operates either an average emission value calculated for all power generators on-line or the marginal emission rate for increase in power demand would be used.

[0053] And so the emission constraints on the Hydrogen Network optimization can be written as:

For an emission$_l$ that must not exceed defined levels,

(∑(Power for Electrolysis from Captive Source$_j$ $f^n(t))_j$ * Emission Rate for Emission$_l$ for Source$_j$) + (_Power for Electrolysis from Grid $f^n(t)$ * Emission rate for Emission$_l$ for Grid) / (Total Hydrogen Production Rate of Network $f^n(t)$) ≤ Proscribed Emission Level for Emission$_l$ per Unit of Hydrogen (t, location of emission)

l=1.....L emission types

Eq.6

j=1.....J captive power generators

where the Emission$_l$ specification may depend on time and geographical location.

and for Emission$_m$ that must not exceed a pre-defined time average:

<<∑(Power for Electrolysis from Captive Source$_j$ $f^n(t))_j$ * Emission rate for Emission$_m$ for Source$_j$) + Power for Electrolysis from Grid $f^n(t)$ * Emission Rate for Emission$_m$ for Grid>>$_{time\ avg}$/(Total Hydrogen Production of Network during Time Period) ≤ Proscribed Time Avg. Emission level for Emission$_m$ per Unit of Hydrogen Produced

m=1.....M emission types

j=1.....J captive power generators

Eq.7

[0054] In markets where emission credits are transferable from power production to fuel production, the emission reductions from captive power sources providing power to grid for which the Hydrogen Network owns environmental attributes can be applied to hydrogen fuel production. In this case

Eq.6-7 would be modified to include emission credits from power generation that could be applied against emissions generated when fuel is produced.

[0055] The Fuel Value function in the Objective Function is the selling price of hydrogen fuel per unit of fuel produced charged to customer less the cost of hydrogen production per unit of fuel produced which depends on cost of available power to the Hydrogen Network and the other variable process costs in operating the particular electrolysis fueling system k ie. cost of water, operating maintenance etc. :

$$\begin{aligned}\text{Fuel Value } f^n(t)_k &= \text{Fuel Selling Price } f^n(t) - \text{Fuel Cost } f^n(\text{Cost of Power } f^n(t), \\ &\quad \text{Fuel Station }_k \text{ Variable Process Costs } f^n(t)_k) \\ &= \text{Gross Margin for Hydrogen Production at Station}_k\, f^n(t)_k\end{aligned}$$

k =1 ...K electrolysers (fuel stations)

Eq.8

The Cost of Power is the cost of power produced by captive sources, which depends on variable costs such as the fuel cost of the generator and charges for grid transmission, plus the cost of power that is purchased from the grid:

$$\text{Cost of Power } f^n(t) = [\textstyle\sum \text{Cost of Captive Power Source}_j \text{ (variable generating costs, transmission charges) } f^n_j(t) + \text{Purchase Cost of Grid Power } f^n(t)]/[\text{Total Captive Power+Amount Grid Power Purchased } f^n(t)]$$

where

$$\text{Total Captive Power } f^n(t) = \textstyle\sum \text{Power from Captive Power Source}_j\, f^n(t)j$$

j=1 .... J captive power generators

Eq.9

Because hydrogen can be stored at the sites, where it is being produced and dispensed to customers, the hydrogen production cost can be minimized by scheduling hydrogen production at times, such as low electricity demand periods on the grid, when grid power costs and grid power generation emissions are lowest.

Within some jurisdictions, the selling price of hydrogen from the Hydrogen Network is another variable, which could be changed to encourage fuel purchases to balance energy supply and demand.

Fuel Selling Price $f^n(t)$ = *Price* f^n*(Customer Demand (t), supply capability at time of week, competition pricing)*

Eq.11

For example the period of lowest electricity demand and as a consequence lowest cost and lowest stress on supply system is typically on weekends and holidays. As a consequence because this a favoured time to produce hydrogen, the price of hydrogen could be lowered to promote consumption during these periods. In this way through the Fuel Value Function and meeting constraint Eq. 5, fuel price can enter into the system optimization to balance energy flows in the Network, and would be part of the schedule information sent to the fuel station network.

The Available Power from Captive Sources in the Objective Function is the total power available from captive sources less the captive power that is committed to the electrolysers for hydrogen production and is the power that could be sold by the Hydrogen Network to the Public Electricity Grid:

Available Power from Captive Sources $f^n(t)$ = *Total Captive Power* $f^n(t)$ – ∑ *[Power for Electrolysis from Captive Power Source*$_j$ $f^n(t)_j$*]*

Eq.12

where

Total Captive Power $f^n(t)$ = ∑ *Power from Captive Power Source*$_j$ $f^n(t)j$

j= 1… J captive power generators

Eq.13

The Grid Electricity Value in the Objective Function depends on the selling price for captive power in the electricity market of the electrical grid, which can also include environmental credits from supply of captive power.

$$\begin{aligned}\text{Grid Electricity Value } f^n(t) &= \text{Captive Power Selling Price } f^n(t, \text{Green Attributes}(t)) \\ &\quad - \text{Cost of Captive Power } f^n(t) \\ &= \text{Gross Margin For Captive Power Sale to Grid } f^n(t)\end{aligned}$$

Eq.14

where

$$\text{Cost of Captive Power } f^n(t) = \sum [\text{Cost of Captive Power Source}_j \; f^n(t)]/ (\text{Total Captive Power } f^n(t))$$

J =1 .... J captive power generators

Eq.15

In some energy markets these credits, called "green tags", may be transferable between the stationary power market and the transportation (hydrogen fueling) market, and hence could be transferred to hydrogen production and used to meet emission constraints in Eq.6-7. In some power markets the emission credit is dependent on the power it is displacing, or the marginal emission rate. Depending on the electricity market design, the ability to sell power into peak demand electricity markets can contribute significantly to the Hydrogen Network, since it is competing with peak power generators which are more expensive, because of poor utilization, and which often have higher specific emission rates.

The optimization is performed over a specific time interval so as to determine an operating schedule and fuel pricing and so as to optimize operating cost subject to constraints of maintaining fuel supply reliability, insuring sufficient fuel is available at each station to meet customer demand and meeting the emission objective that the hydrogen produced has specific and verifiable emission characteristic over the whole production cycle on an instantaneous or time average basis as proscribed by the emission standard.

The same scheduling algorithms can be used in longer running hypothetical demand scenarios to determine the mathematically optimized number, size and location of fueling outlets needed to satisfy demand in a region and the necessary commitment to invest in captive electricity generation as well as the type of generation as it relates to the specific emission profile required to insure specifications of the environmental label are met.

The fueling of hydrogen vehicles presents a potentially large load on the grid. Projections for North American markets have shown that electrical power required to fuel a fleet of fuel cell vehicles equivalent to the gasoline powered vehicles on the road today would double the amount of energy handled by the grid, and so the power transfers of the Hydrogen Network could have a huge impact on the grid. Because the electrolysers can act as "responsive loads" reacting very quickly and their production rate and hence power range can be varied over a wide range, the Hydrogen Network under control of the Hydrogen Network Controller can provide ancillary services to the electricity grid such as providing operating reserves and even generator control services to insure electricity network stability. These ancillary services if contracted and paid for by the grid operator would be provided at the request of the Public Grid Operator and would act as conditional constraints on the system.

Typically the request for Grid Power Supply Change would in the form of directive to increase or lower fuel production at specific hydrogen generators or groups of generators over time t to t +Δt depending on geographical location hence through :

$$\textit{Grid Power Supply Change at station}_k(t+\Delta t) = [\textit{Rate of Fuel Production } f^n(t+\Delta t) - \textit{Rate of Fuel Production } f^n(t)]_k * [\textit{specific power consumption for hydrogen production at station } f^n(t+\Delta t)]_k.$$

Eq.16

where the new Rate of Fuel Production at time $t+\Delta t$ is now fixed for the period the request is in effect. Applying this constraint other resources on the network may need to adjust schedule to meet production constraints.

[0056] For example during the daily ramp up and ramp down in electricity demand, the Hydrogen Network can disengage and engage electrolysers either making power available to the grid from captive generation or reducing the electricity supply by absorbing power from the grid. Because of the responsiveness of these systems the Hydrogen Network can earn additional revenue in these periods from the Public Electricity Grid operator, and because of the distributed nature of hydrogen production units in the Hydrogen Network, they can provide ancillary services to individual generators as well as transmission lines addressing transmission capacity constraints. The services provided by the electrolysers as "responsive loads" in the Hydrogen Network can be supplemented by hydrogen powered electricity re-generation, which could be available at the hydrogen fueling stations and which also could be under the control of the Hydrogen Network Controller.

[0057] In some cases the request may not be load specific. In this case the provision of these services would be guided by the same optimization in Eq.1-15 in terms of calculating value for captive energy flows however in this case if contracted to provide services in terms of shedding load or increasing loads the Network must react to the grid operator request to meet these requirement thus becoming an instantaneous operating constraint on the system; modifying Eq.4.

$$\text{Grid Power Supply Change at station}_k(t+\Delta t)= \{\sum[\text{Power for Electrolysis from Captive Power Source}_j\ f^n(t+\Delta t)]_j + \text{Power for Electrolysis from Grid } f^n(t+\Delta t)\} - \{\sum[\text{Power for Electrolysis from Captive Power Source}_j\ f^n(t)]_j + \text{Power for Electrolysis from Grid } f^n(t)\}$$

[0058] For example if the Hydrogen Network is contracted to provide operating reserves and the grid operator requests a Grid Power Supply Change but not from specific loads then the Hydrogen Network Controller would increase Captive Power Selling Price in Eq. 14 reducing fuel production in Eq. 1 until sufficient power is made available to make up the power which the Network has been contracted to supply. If on the other hand the Grid operator requests that the Hydrogen Network absorb a power supply surge, the Hydrogen Network Controller responds by reducing the value of Cost of Grid Power $f^n(t)$ in Eq. 9 increasing fuel production in Eq. 1.

[0059] In the case of the hydrogen network providing ancillary services, the operating schedule would be conditional on demands from the grid operator and so contingencies in terms of storage capacity and the amount of fuel stored to meet customer demand in Eq. 5 and emissions in Eq. 6-7 would be needed to insure the Network operates within these constraints.

[0060] Under highly constrained market conditions hydrogen fuelled power regeneration or back up power units could play the role of captive power sources, in cases such as providing back up power locally to grid under emergency conditions or if there is a demand spike in the electricity market. In this case the regenerative systems act as captive power sources, which are run when the Captive Power Selling Price exceeds the variable cost of regenerating power (Eq.9), based on, fuel cost = selling price of hydrogen, (Eq.11) and hence under these conditions when operating the unit is profitable. This may occur even while hydrogen is being produced on the Network. For example when power demand on grid exceeds available supply but one or more fueling station on Network have insufficient inventory to meet demand, Eq.5, and so must produce fuel. In this case a virtual transfer of hydrogen fuel from one station to another can be transacted through the electrical grid.

[0061] In the preferred embodiment the Hydrogen Network would be a wholesale buyer and seller of electricity and would operate as a hydrogen-electricity utility having captive sources of energy with defined emission characteristics which it controls either through bi-lateral contracts with the electricity generators or which it owns out-right. In this way the Hydrogen Network owns the environmental attributes of specific power sources generating electricity in a specified period. Because the system-wide hydrogen production requirements are significant given that hydrogen is being used to fuel a large fleet of hydrogen vehicles, the energy transfers into and out of the general electricity grid will have a significant impact on energy balances in the public electricity supply.

[0062] The preferred embodiment for the physical layer of the Hydrogen Network, shown in Figure 1, consists of various captive clean sources of electricity (31) connected to a Public Electricity Grid (33), various different hydrogen users (38),(41),(40) in different geographical locations, which are served by hydrogen supply systems controlled by Unit Controllers (32) controlling Electrolysis Hydrogen Production (35) connected to the same electrical grid (33) to produce hydrogen on-site, filling storage tanks (39) and controlled by a single point Hydrogen Network Controller (34) which exchanges data with each resource over an information network, the data carrier being a telephone line (36) or wireless device (37) or the grid itself (33). The hydrogen users which can be fuelled by the network can include fast and slow fueling of hydrogen vehicles (38), hydrogen fuel for emergency power systems (41) satisfying local or grid demands, industrial processes requiring hydrogen (40) and combinations of these systems. The Hydrogen Network Controller (34) exchanges data with the Electricity Grid Network Operator (42) regarding power transfers between the grid electricity supply and the Hydrogen Network, these transfers being supply of power from Grid generators (43) to hydrogen users (32) or supply of captive power (31) to Grid Loads (41).

[0063] In the preferred embodiment the captive sources of electricity generation are a combination of wind and nuclear power and other forms of clean power generation for which it is difficult to regulate electricity output to match general electricity demand on the grid. A typical daily electricity demand profile for the Public grid is shown in Figure 2. The peak in demand (61) occurs between 11:00 AM and 5:00 PM. The power available from the captive generators: wind (71) and nuclear (72), shown in Figure 3, has a supply characteristic different than the electricity demand profile in Figure 2.

[0064] In Figure 1 the Hydrogen Network Controller (34) would collect data from unit controllers 1...k (32) on hydrogen demand from Hydrogen Users 1..K, (38,40,41), hydrogen inventory (amount of hydrogen stored at each site, Hydrogen Tank 1..K) (39) and system capability data (equipment availability, specific energy consumption) from the geographically distributed hydrogen generators, Electrolysers 1...K (35) controlled by the Hydrogen Network as well as data from energy power availability from captive power generators, Captive Power Generators 1...J (31) over the next schedule period (Figure 3), such as the “day-ahead”, defining a time horizon for control actions. The scheduling of Network resources would coincide with planning by the general electricity grid operator (42) in order to negotiate transactions on grid with other power producers, Grid Generators 1..m, and power marketers and distributors to buy and sell power. The Hydrogen Network Controller would use this information to determine an optimal schedule for producing hydrogen in the electrolysers (35) and supplying captive power (31) to Public grid (33) to meet general electrical demands, Grid Loads 1..n, (41) taking into account mismatch between captive power supply Figure 3 and the general demand profile for the Public grid Figure 2.

[0065] The data flows for the Hydrogen Network controller are shown in Figure 4. Captive electricity generation forecasts and an update on specific emission rates from each power generator (1), along with data from the hydrogen generators and hydrogen application regarding user demand (2), system status/capability data (4) (equipment availability, updated energy consumption) is collected along with amounts of hydrogen in inventory at the different locations as determined from the pressure, temperature and size of hydrogen storage tanks (3). Based on demand models (2) which are updated based on historical data regarding hydrogen consumption determined by monitoring storage tanks (3) and hydrogen generator (2) the Network Controller (7) would calculate a production schedule (Rate of Fuel Production$_k$(t)) necessary to meet demands on a period forward basis such as a "day-ahead" schedule using Eq.1 – Eq. 15. The controller would exchange data with Public Electricity Grid operator (8) to get data on the electricity market (6) which is typically created one-day ahead and decide how much grid power it should buy (10) and captive power it should sell (11) in order to its meet hydrogen production schedule, emission objective, and maximize the contribution of captive power sold to the Public grid. Typically the peak in the demand profile (61) in Figure 2 is the point of highest real-time marginal costs and emissions on the Public Grid since typically fossil fuel powered peak generators are used, and so provides a favourable market for selling clean captive power whereas in off-peak demand periods (62) the real-time cost of power measured by marginal cost is very low presenting a buying opportunity to the Hydrogen Network. The Hydrogen Network controller would negotiate the power purchases (10) and sales (11) with the grid operator and determine the optimal production schedule for each hydrogen generator in the Network (14), and send the schedule to each electrolyser ahead of the start of the production period. The Hydrogen Network Controller may further optimize system by adjusting fuel price which would be included in the production schedule. The Hydrogen Network Controller would then monitor captive electricity supply (1), hydrogen demand (2), hydrogen production (4) and inventory (3) at the different fuel stations and make corrections as required.

[0066] For example consider the case when the captive power system is a nuclear power plant. In this case captive power availability is a constant power output over the schedule period Figure 5(a). The hydrogen demand model shown in Figure 5(b) for hydrogen production for vehicles, peaks in the morning and a larger peak occurs in the afternoon (51) extending into early evening reflecting time when people are not working and can fuel their vehicles. The general market for electricity is expected to follow the profile in Figure 2 and so the Hydrogen Network controller will operate the hydrogen production systems in the period of low electricity demand and sell power from the nuclear power plant in the peak period and so the production schedule will appear as in Figure 5(c) and the schedule for captive power sold to the Grid appears in Figure 5(d). The hydrogen produced during non-peak periods will be stored in hydrogen storage tanks at the different fuel station locations. In this case the emission profile for the hydrogen produced will be based on the emissions from the nuclear power plant, and so will be essentially zero, Figure 5(a).

[0067] In another case the primary hydrogen demand is fueling a fleet of commercial vehicles. Refueling commercial vehicles may have a very well defined fueling period at night Figure 5(e), typically a low electricity demand period, allowing direct or slow fill of vehicles at this time, hence reducing storage requirements.

[0068] By being able to utilize energy on a variable and intermittent power basis the Hydrogen Network can provide energy management services to increase the penetration of nuclear power into the grid supply during peak demand periods. This will in the long run displace less efficient/higher emission fossil fuel powered generators and increase power option availability for the Hydrogen Network while reducing emissions from power generation for grid electricity.

[0069] In another Hydrogen Network shown as Wind-Hydrogen Network in Figure 6 (a) , wind power turbines (80) are the captive power generators. The wind resources have a forecasted power availability profile shown in Figure 6 (b). In this case the Network controller can sell a well defined block of the power generated to the grid Figure 6(c) and use the remainder to meet hydrogen production requirements absorbing the variable hydrogen production into hydrogen storage Figure 6(d). The Hydrogen Network Controller (84) can regulate the energy flow to the grid hence saving the grid operator the cost of having to handle the dynamic matching of supply and demand. The hydrogen storage is sufficient to insure that exactly the amount of energy defined by the controller is delivered to the grid. In the case of wind or solar day-ahead forecasts would be used to predict power availability. Monitoring the rate of power production the Hydrogen Network Controller can make real-time adjustments to hydrogen production units to make up the difference between actual and predicted production with the hydrogen production surpluses or shortfalls carrying forward into the next day schedule.

[0070] In the particular case when wind resources are extremely variable a dump load is needed to absorb excess electricity production. In the case of hydrogen systems excess hydrogen production beyond what could be stored in tanks (83) could be injected into the natural gas distribution system (81) and heat value of hydrogen could be recovered. In this way the maximum storage capability can be extended in the optimization above relaxing the constraint in Eq. 5. An emission credit could be earned for reducing CO_2 emissions by substituting hydrogen for methane.

[0071] By being able to utilize energy from variable, intermittent renewable power sources, and provide energy management to offset their unpredictable nature, the Hydrogen Network can increase the penetration of the clean renewable energy resources into the mix of power generation powering the grid. This will in the long run increase power option availability for the Hydrogen Network, lowering costs and the need for hydrogen storage systems

[0072] In another scenario at particular times the demands of the Hydrogen Network may exceed the power available from captive generators. In this case the Network operator needs to purchase power from the grid and would contract the supply of electricity from the electricity grid operator or from generators on the grid. For example if there were a large number of fleet vehicles in many fleets fueling at night having the general hydrogen demand profile Figure 5 (e) and if the captive generator was a nuclear power plant with power availability Figure 5(a) the Hydrogen Network would sell captive power during the day Figure 5(d) and use its captive power source at night to make fuel. In this case however the amount of captive power is insufficient to meet the demand of hydrogen production and the extra power needed to produce fuel during this period would be purchased from the grid Figure 7(a). Depending on the contractual details the emissions for this power delivered could be assessed on a time-average system-average basis, and so could be and for this case is assumed to be constant over schedule. This constant value would be used to calculate the average emission for hydrogen produced by captive and grid sources to insure emissions are within the limits of the specification Figure 7(b). By providing clean captive power in peak demand periods the Hydrogen Network Controller would contribute to reducing the specific emission rate (emissions per kWh) of the grid. This characteristic can be further exploited in shifting the power demand of the Hydrogen Network from captive to grid generators to take advantage of lower power costs in low demand periods. Because in many control areas nuclear power is the base generation system, grid emissions are lowest in low demand periods. These two properties can be combined to optimize the operation of the grid to shift demand into lower demand/low emission periods and shift clean captive power generation into higher cost/higher emission periods. This is illustrated by Figure 8(a)-8(d). Figure 8(a) shows the marginal price of power set by the grid operator or electricity market operator, which following the demand profile in Figure 2, is reflective of marginal cost of production or the price, which the grid power generator is prepared to take. If the Grid operator acts as a market operator, this curve sets the marginal price plus transmission cost that the Grid operator representing grid loads will buy power from captive power generators in the Hydrogen Network and a marginal price at which power can be purchased by the Hydrogen Network for hydrogen production from the grid operator representing grid generators. Associated with these price curves is a specific emission rate for the grid, Figure 8 (b), which in general follows the demand curve in Figure 2, because as the demand on grid generation increases the emission rate generally increases, Figure 8(c), because less efficient/less clean peaking generators are employed. In the power transactions with the Hydrogen Network Controller as shown in Figure 5(a), Figure 5(d), Figure 7(a) , the grid operator can lower the specific emission rate in peak periods, Figure 8(d) and the Hydrogen Network Controller can earn higher revenue selling power at the higher marginal grid power price at peak times, making up power as needed for hydrogen production by purchasing power in off-peak periods, thereby lowering hydrogen production costs.

[0073] The action of the Hydrogen Network Controller would in this case lower emissions for grid power generation while operating the Hydrogen Network inside the emission limit for hydrogen production for fuel. In some markets the credit for emission reduction for supplying power to the Public Electricity Grid would be expressed in added revenue through emission credits which can be traded in a public market, in other markets the emission reduction from the power generation could be transferred as an emission credit to the production of hydrogen. In such markets the emission attributes of power generation could be transferred from one time to another. This would provide additional incentive to the Hydrogen Network to provide clean captive power to the grid during peak times, which in effect would displace high emission power and reduce emissions produced by the whole energy system as shown by taking area under the Specific Emission Rate shown in Figure 8 (e).

Working out this example quantitatively in a case study:

We assume that Electricity Demand (Figure 2) results in two-tier electricity rate for power from the Public Grid:

8 cents per kWh in peak period 11:00 AM to 5:00 PM
4 cents per kWh in "off-peak" period 5:00 PM to 11:00 AM

which could be the price at which the Hydrogen Network could buy power from the Public Electricity Grid. The specific emission rate will vary with time as a number of different power plants makeup the Public Grid generator mix. For reporting, the emission rate is taken as the historical average and since grid is mix of nuclear and coal and the average specific emission rate is around 10 gm per kWh such as shown in Figure 7(c).

Furthermore we assume there is a "postage stamp" transmission charge of 2 cents per kWh to wheel power from the generator to the user, and so selling power to the grid, the Hydrogen Network could expect to be paid the market price less the transmission charge:

6 cents per kWh in peak period 11:00 AM to 5:00 PM
2 cents per kWh in "off-peak" period 5:00 PM to 11:00 AM

Now assume that the Hydrogen Network owns rights to 50 MW of nuclear power which is available on a continuous basis such as Figure 5(a) and assume the full cost of power is 3 cents per kWh at the gate and the nuclear power plant has a specific emission rate of 1 gm per kWh such as shown in Figure 7(b).

Furthermore assume from demand analysis that the selling price for Hydrogen fuel is \$3.50 per kg (Eq.11), the costs of hydrogen production at the fuel station less electricity cost are \$0.90 per kg and it takes 50 kWh to produce 1 kg of hydrogen.

Therefore the Fuel Value Function (Eq.8) for hydrogen production using captive power:

[\$3.50 – (\$0.90+ (50kWh * (3 +2) cents per kWh))] per kg = \$0.10 per kg for hydrogen production using grid electricity in the peak period

[\$3.50 – (\$0.90 + (50kWh * 8 cents per kWh))] per kg = - \$1.40 per kg

for hydrogen production using grid electricity in the non-peak period

[\$3.50 – (\$0.90 + (50 kWh *4 cents per kWh))] per kg = \$0.60 per kg

and for the Grid Value Function (Eq.14) for selling captive power at the different times:

(\$0.06 - \$0.03) = \$.03 per kWh during peak periods

(\$0.02 - \$0.03) = \$-.01 per kWh during non-peak periods.

Now looking at the emission rate associated with fuel production:

(10 gm/kWh * 50 kWh/kg) = 500 gm/kg-H2 using power from public grid
(1 gm/kWh * 50 kWh/kg) = 50 gm/kg-H2 using power from captive power

Now if we assume that the emission limit for the fuel proscribed by the emission label is 95 gm/ kg and that this limit cannot be exceeded at any time in the fuel production process, following constraint in Eq. 6:

$$(a * 500 + b * 50) \text{ gm/kg} \leqslant 95 \text{ gm/kg}$$

where

a = fraction of hydrogen production rate powered by public grid

b = fraction of hydrogen production rate powered by captive power

And so the emission constraint in Eq. 6 can be expressed as the constraint of the maximum penetration of public grid power into the Hydrogen Network being 10%.

Now looking at the day-ahead schedule to meet production requirements of fueling a large fleet of commercial vehicles at night (Figure 5(e)) requiring 20,000 kg of hydrogen fuel (Eq. 3) will require 1,000 MWh of electric power (Eq.2). The maximum production rate from captive power is 1,000 kg/h and so over the non-peak period it can produce 18,000 kg per day.

The Hydrogen Network controller would take the data above and determine a production schedule maximizing the Objective Function (Eq.1) over the 24 h period:

V(t) : MAX{∑[*Rate of Fuel Production* $f^n(t)$* *Fuel Value* $f^n(t)]_k$ + ∑[*Available Power from Captive Power Sources* $f^n(t)$ * *Grid Electricity Value* $f^n(t)]_j$}

Subject to the constraints:

Limit grid penetration such that *power for electrolysis from grid* $f^n(t) \leq$ (50/9 =) 5.6 MW

Limit captive power such that *power for electrolysis from captive power source* ≤ 50 MW

System must produce 20,000 kg in 24 h period.

From inspection of the equations above, the system will be optimized if the following schedule is used for hydrogen production:

Hydrogen isn't produced during peak period and captive power is sold to grid for peak period (11:00 AM to 5:00 PM)

The captive power sold to public grid earns revenue (50,000 kW * 6h * 6 cents/kWh) =$18,000 over 24 hours plus reduces grid emissions by (50,000 kW * 6 h *(10-1)) gm/kWh = 2.7 tonne., which if there is a public market which trades emission credits could be used to earn additional revenue or in same market can be "banked" and applied against future fuel production.

While for hydrogen production in the off-peak, the 50 MW of captive power and 5.5 MW of grid power, produces 1,000 MWh in 18 hours enough to produce 20,000 kg of hydrogen in 24 hours and because the grid power intensity is less than or equal to the constraint value the emission objective is achieved.

And following Eq.9:

Cost of Power $f^{n}(t)$ = 0.9* ($0.10 per kWh* 50 MW)+ 0.1 *($0.60 per kWh *5.5 MW)
=$4830 /h

then

Fuel Value $f^{n}(t)$ = (.9 * $0.10 + .1*$0.90) = $0.18 per kg of H2 over the 20,000 kg produced in 24 h.

and so evaluating **Eq.1**:

V(t) = [(20,000 kg* $0.018 per kg) + (300,000 kWh*$0.03 per kWh)]

= $12,600 per day plus grid reduction of 2.7 tonnes of emissions.

This production schedule maximizes value of the resources in the Hydrogen Network.

[0074] In another example of a different type of Network configuration, Figure 9, a set of hydrogen users (91) in the Hydrogen Network such as a community of homes or housing complex, may lie inside a physical zone (96) which are powered by specific captive power systems (92) on a "private" electricity micro-grid (93) maintained by the community such that some but not all energy needs of the community are met by the captive power systems inside the zone. A zone controller (94) is used to regulate energy flows for hydrogen production as well as other load demands in the zone including hydrogen fuel production. In this case the Hydrogen Network Controller (95) would exchange data regarding transfers of energy into and out of the zone (96) with the zone controller (94) and the zone controller would balance and optimize the system with in its control area to achieve a measurable emission level for hydrogen produced inside the zone.

[0075] In another market the framework for optimization could apply to transfer of “green tags” or the rights to environmental attributes of the power generated inside the Network and used for hydrogen production. In this case the Hydrogen Network would purchase the “green tags” for the entire output of a “clean power” generator over a certain period of time preferably including periods when the Public Electricity Grid marginal emission rate is high. Based on the argument that the “clean power” displaces marginal power emissions the value of the “green tags” are based on the marginal or average emission rate at the time “clean power” was generated. The Hydrogen Network controller would then decide whether to produce hydrogen and apply green tags against the hydrogen produced to meet the specification of the environmental label or not produce hydrogen and sell green tags to buyers in the electricity market for obtaining credit to be applied in off-peak periods. Additional power could be purchased from grid during period of low emission rate to make up short fall. For example during a power peak when power is generated by an inefficient coal plant, the Hydrogen Network Controller would decide not to produce hydrogen and apply environmental attributes to electricity market and thereby gain credit for displacing coal fired generation while at night during period of low grid emissions when the grid is supplied by cleaner base load generation such as nuclear power, he might purchase power from the grid to produce hydrogen. The net effect from the purchase of green tags is that hydrogen of specific emission levels is produced while at the same time grid emissions are reduced.

[0076] Assuming the public grid has the General Electricity Demand Profile in Figure 2 and Specific Emission Rate shown in Figure 8(b), the power output of the clean power generator being effectively a zero-emission power source would provide a marginal emission reduction equal to the marginal emission rate of the grid. By producing hydrogen in the non peak period the

Hydrogen Network controller can apply marginal emission reductions in peak times against hydrogen produced in non-peak times to achieve the required environmental label. Illustrating this transaction in a numerical example, based on the marginal emission rates if the marginal emission rate of the Public grid during peak times is 1000 gm per kWh, and the marginal emission rate in the non-peak period was 100 gm per kWh a net emission reduction of (1000-100 = 900) gm per kWh is realized by the whole system for each kWh transferred from peak to non-peak times. To realize this gain, the Hydrogen Network would purchase green tags from the output of the clean power generator for a period of time over the full day which would encompass both peak and non-peak periods. The green tags that apply to peak times earning credits would be used in non-peak times so that objectives of specific emission rates from hydrogen production would be achieved by adding emission credits in Eq 6-7. The Hydrogen Network Controller would optimize hydrogen production schedule using “green tags” in a similar way to captive power in a competitive electricity market in Eq. 1 subject to emission constraints in Eq. 5 and Eq. 6-7.

[0077] The optimization of the resources in the Hydrogen Network according to methods proscribed will also impact the design and layout of the physical resources particularly through minimizing transmission charges and maximizing effectiveness of power regeneration systems. Generally speaking the fueling stations constitute a distributed load which will be located in the same locations as general electrical demand and so, as it is unlikely that the power demand of fuel stations will exceed transmission capacity at a given location and that the fuel stations themselves will operate in periods of low electricity demand, that special transmission allowances or arrangements with grid will be needed beyond those already in place. Also in designing the network there is an inherent trade-off between production capability and storage.

[0078] Based on the system characteristics however, the Hydrogen Network designer can further optimize the design of the network based on following factors, which are a consequence of the Hydrogen Network and optimization:

[0079] Locating the hydrogen generation at points on the electricity grid or network to relieve periods of excess supply over demand, or instability where a renewable energy source is connected and making available a hydrogen application that can absorb the hydrogen such as injection of hydrogen in a natural gas pipeline;

[0080] Locating hydrogen generation and / or hydrogen storage and regeneration at points on the grid or network to relieve periods of excess demand for fuel, power and / or heat;

[0081] Locating hydrogen generation and / or hydrogen storage at points on the grid where the capacity of the grid itself is constrained relative to the available supply or demand for power;

[0082] Locating hydrogen power regeneration at locations to distribute operating reserves and improve system reliability to avoid need for committing larger units of generation;

[0083] Providing hydrogen fuel from the distributed network of hydrogen energy storage devices as stores become depleted or additional demand is expected; and

[0084] Providing a supplemental load to permit base load plants to operate at their optimum efficiency and lowest emissions during periods of low demand.

[0085] The Hydrogen Network operator could also work closely with the other power generators on the Public grid to make power purchases bilaterally to improve emissions through demand management of specific generators such as natural gas fired generation where a significant drop in efficiency occurs when power levels are reduced and hence a significant increase occurs in specific emissions (emission gm per kWh). By increasing loads through hydrogen production the generator is more efficient and hence produces lower specific emissions. In this way the Hydrogen Network can also act to improve the efficiency of the Public grid.

[0086] These actions could be formally contracted by selling ancillary services to the grid. Because the Hydrogen Network can adjust energy flows between captive power plants and hydrogen production in a very precise fashion and on a "real-time" basis the system can provide short-term operating reserves to the grid and even "spinning reserves" by making a certain proportion of the demand for fuel production a "responsive" load. In this way, in the event of outage of a generator or transmission line and the Hydrogen Network is contracted to provide operating reserves, the Hydrogen Network controller would be notified and would turn down the rate of hydrogen production to make power available as required. Similarly in dynamic control when load is picking up at the beginning of high demand periods or during periods when load is dropping off the Hydrogen Network can operate as a variable power generator to facilitate the ramp up of power plants. For some forms of generation that are currently used such as coal powered generators this will reduce start up times and increase the efficiency of operation, resulting in lower specific emissions. In fact if the electrical load is large enough, the Hydrogen Network could be used to dynamically adjust load in the electrical network to improve efficiency and reduce cost through potentially maintaining a higher level of control than other wise available by adjusting output of conventional power generators. The tighter control of the grid will result in efficiency improvement benefits which will accrue to the Hydrogen Network and which also lower specific emission rates for the grid. These actions could be enhanced by regenerative systems that can be part of the Hydrogen Network through "hydrogen energy stations" which incorporate power regeneration from hydrogen fuel with hydrogen production.

[0087] The list of ancillary services provided by the Hydrogen Network could include: "spinning" type reserves (<1 minute dispatch time), operating reserves, emission reductions (i.e. air quality emergency) and to some degree generator control as well as relieving local grid congestion.

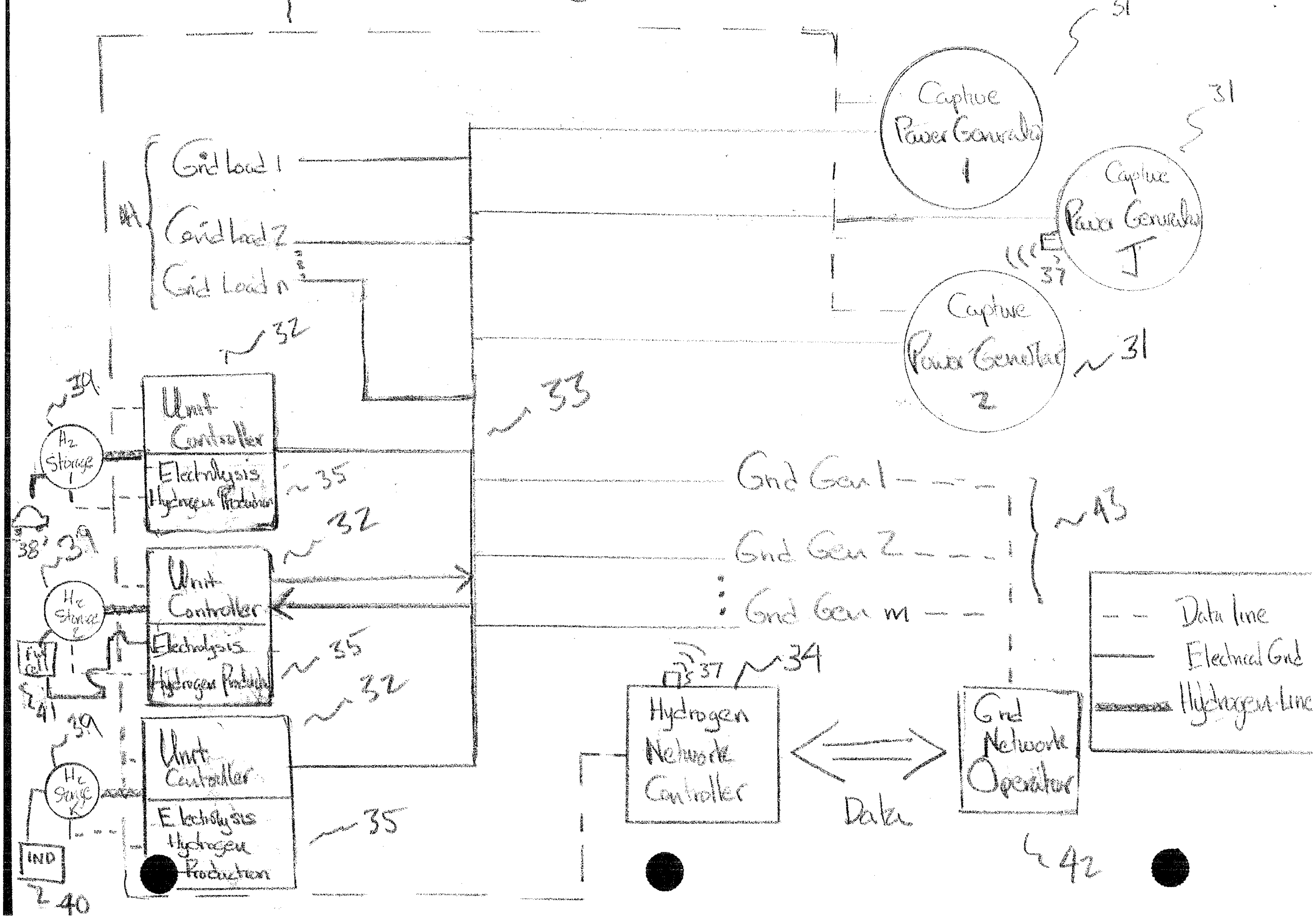
[0088] The provision of ancillary services could contribute significantly to the value of the Hydrogen Network. The ancillary services themselves would be service requests from the grid operator which having been previously contracted to the grid would act as constraints in the optimization in Eq.1 The data flow diagram, in Figure 4, would be modified as shown in Figure 10 with the addition of data input (15) from the Grid Operator (8) for the Hydrogen Network Controller (7) to respond to Ancillary service requests (15).

[0089] An ancillary service request would act like a higher level or "overriding" constraint on the Network optimization constraint either through Eq.16 specifying a certain load be increased or shed in the Hydrogen Network or if non-specific change in power level through optimization of the resources subject to changing power available to grid.

[0090] The impact on design of the Network so that the Network can provide ancillary services, would be an increase in storage capability in the system and a general increase in inventory to account for conditional constraints and insure fuel supply reliability.

[0091] The above ideas describe a model for implementing a Hydrogen Network with definable emission characteristics, which can be implemented on a Public Electricity Grid based on a single point Hydrogen Network Controller, the Hydrogen Network, being defined by the primary energy sources controlled by the Network, would act as a hydrogen-electricity utility on the grid.

Figure 1 - Hydrogen Network (Physical Layer)



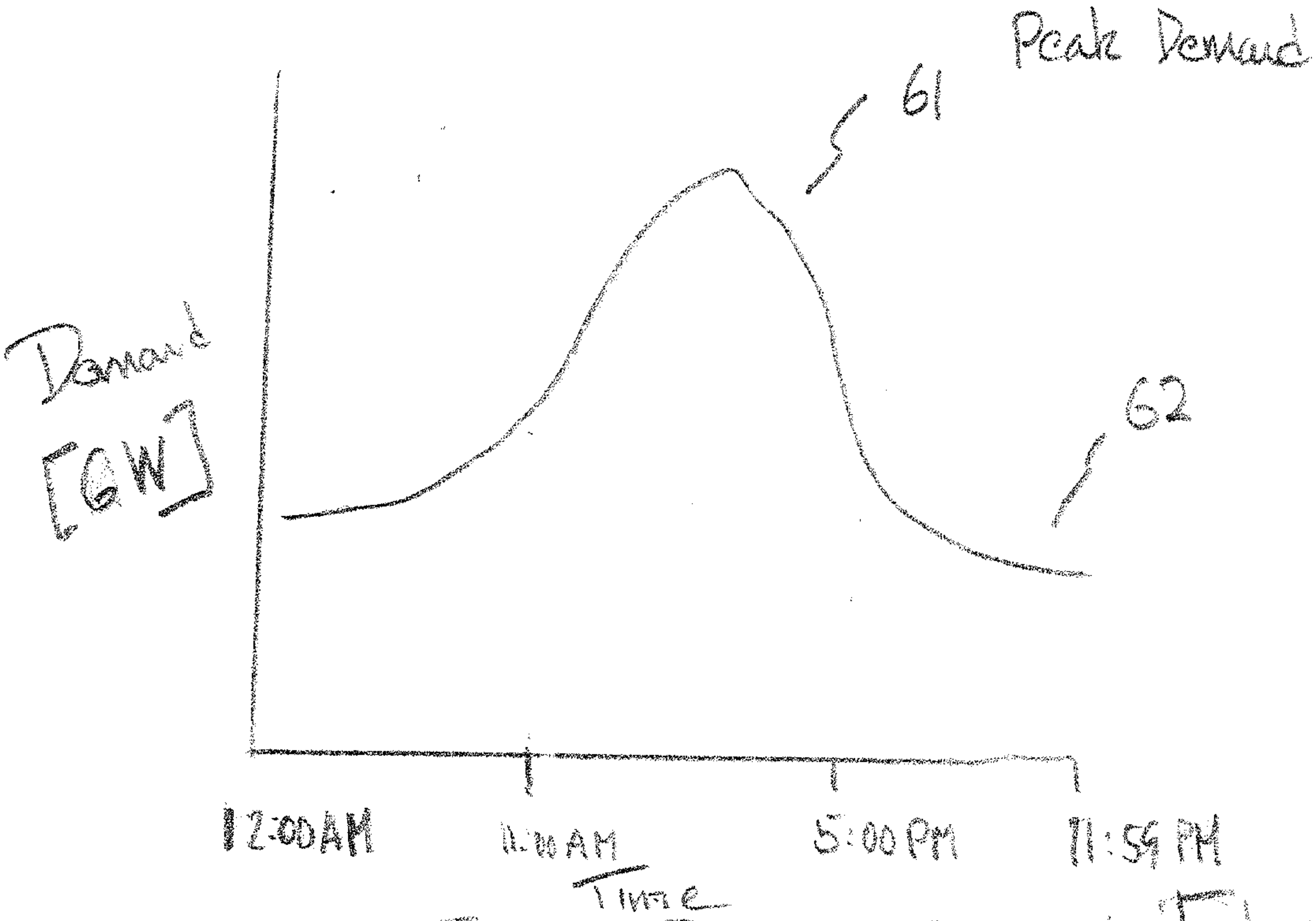


Figure 2 - General Electricity Demand Profile

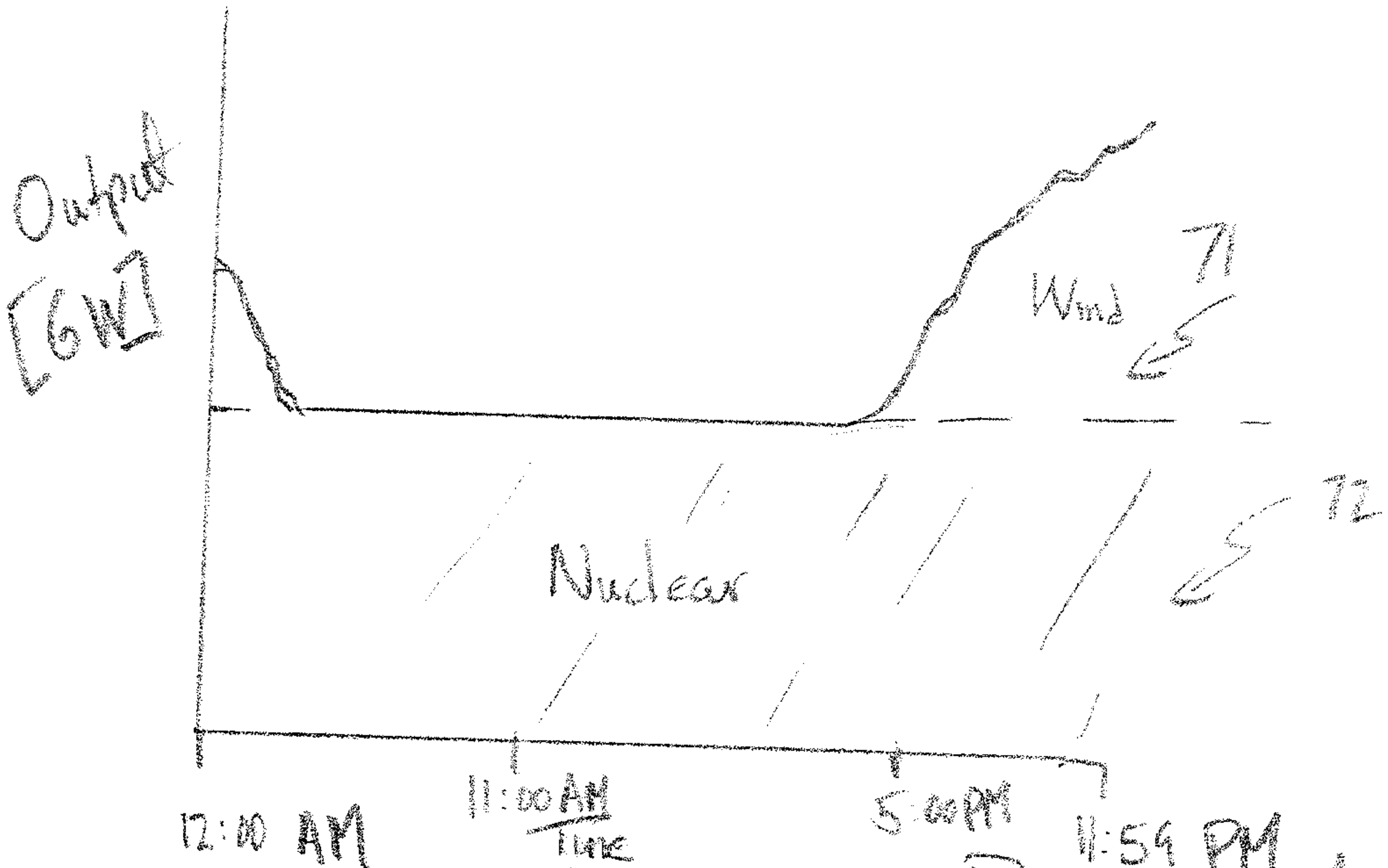


Figure 3 - Power Available from Captive Generators

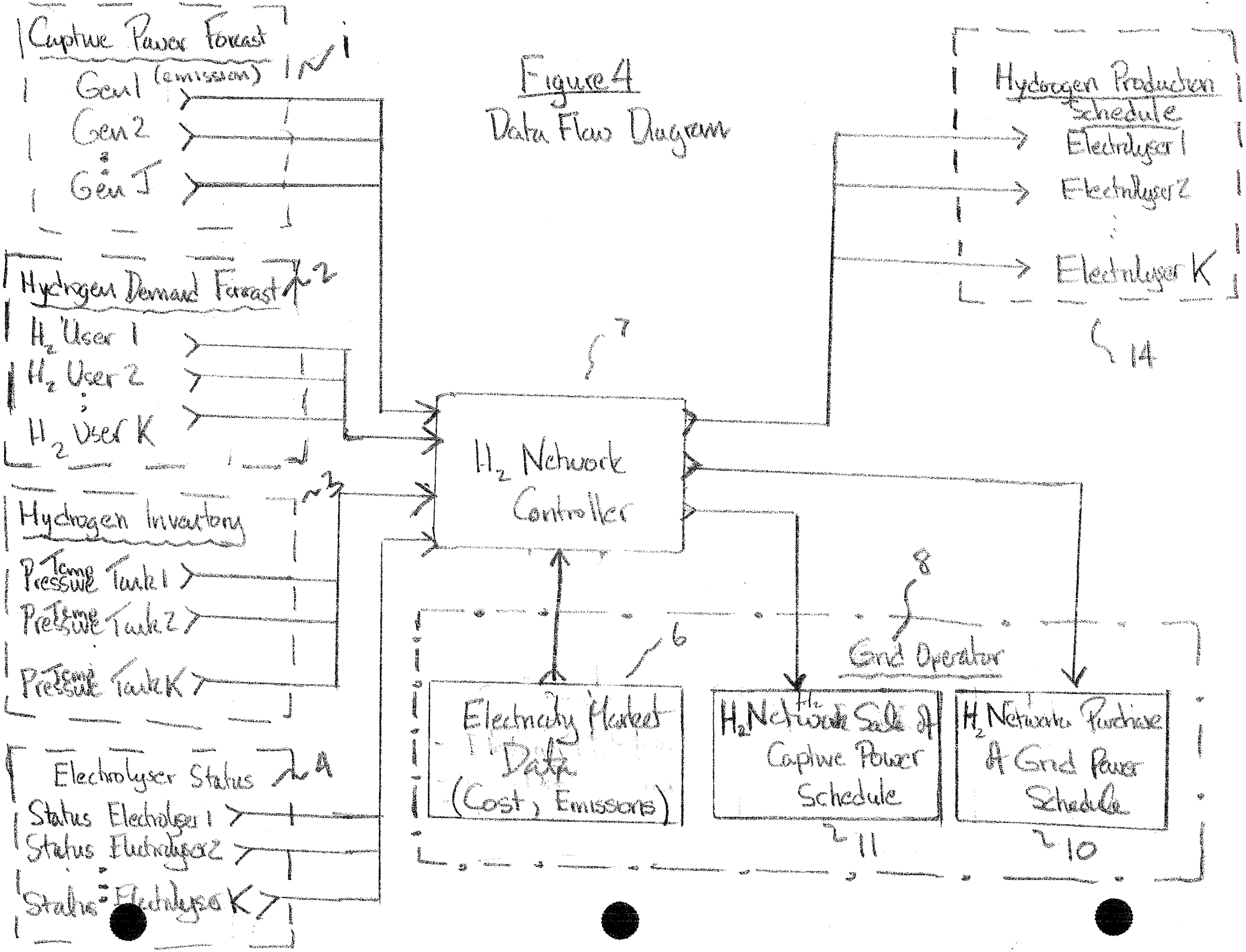


Figure 4
Data Flow Diagram

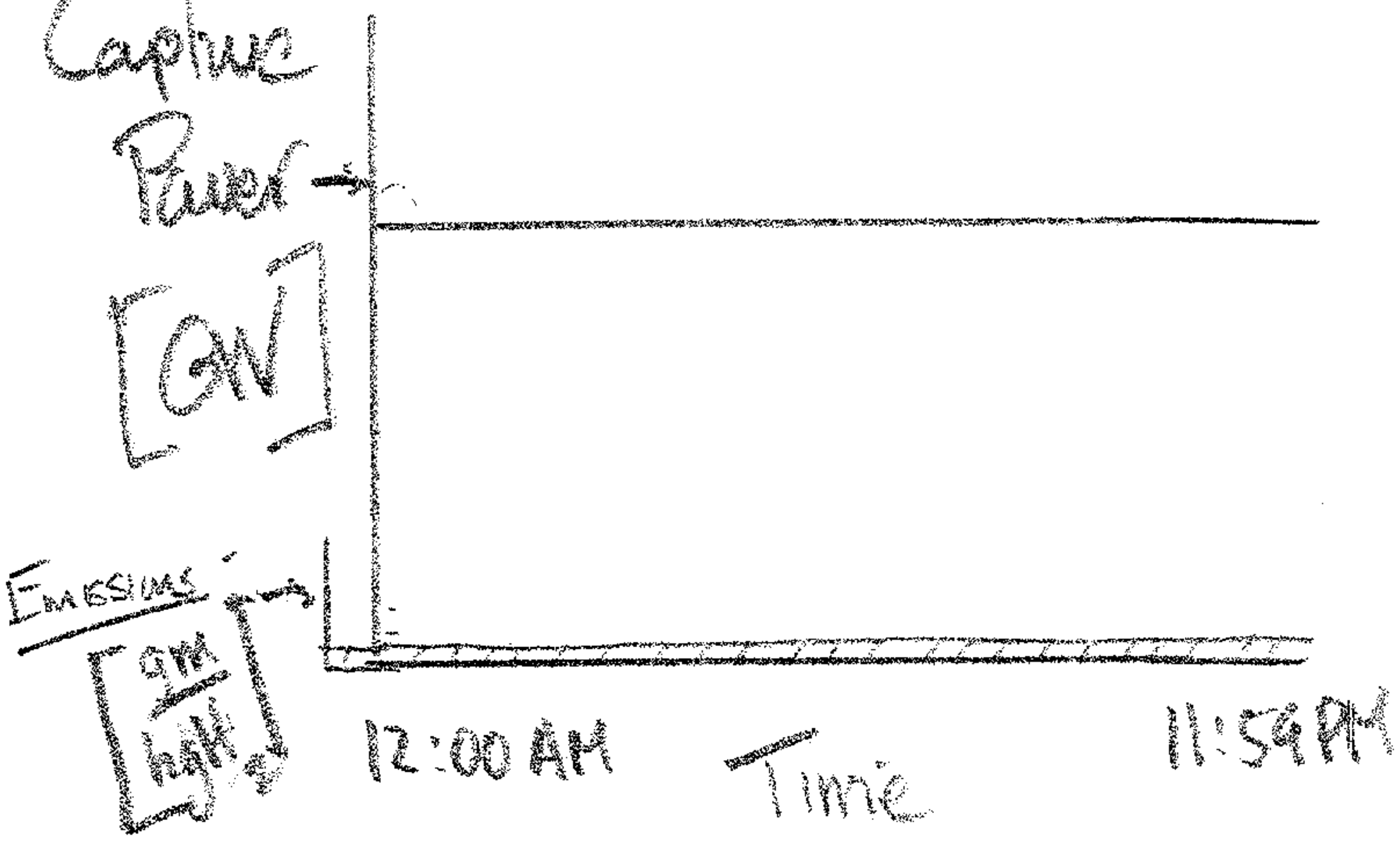


Figure 5(a): Capture Power Available from Nuclear Power Plant

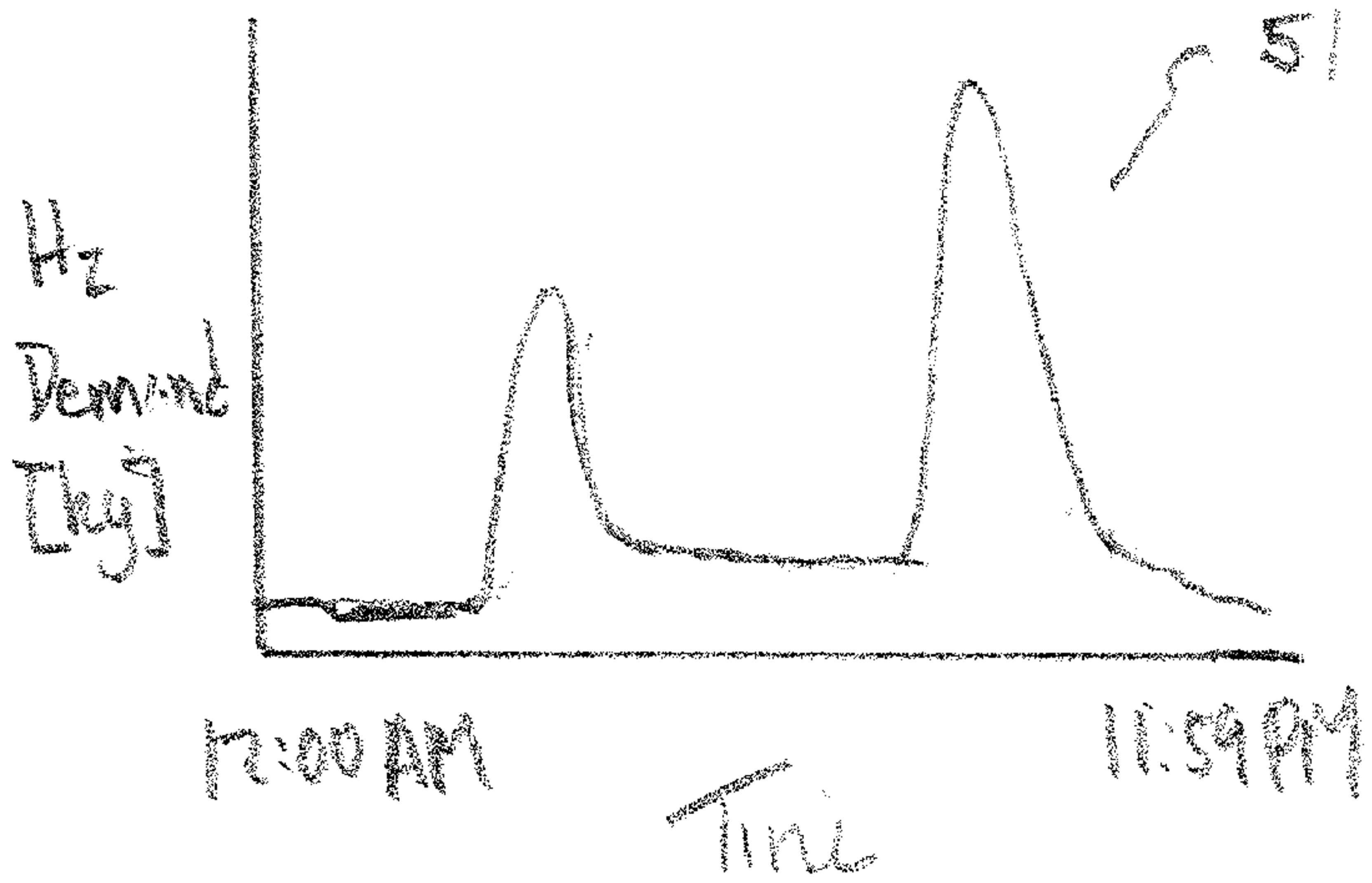


Figure 5(b) Hydrogen Demand

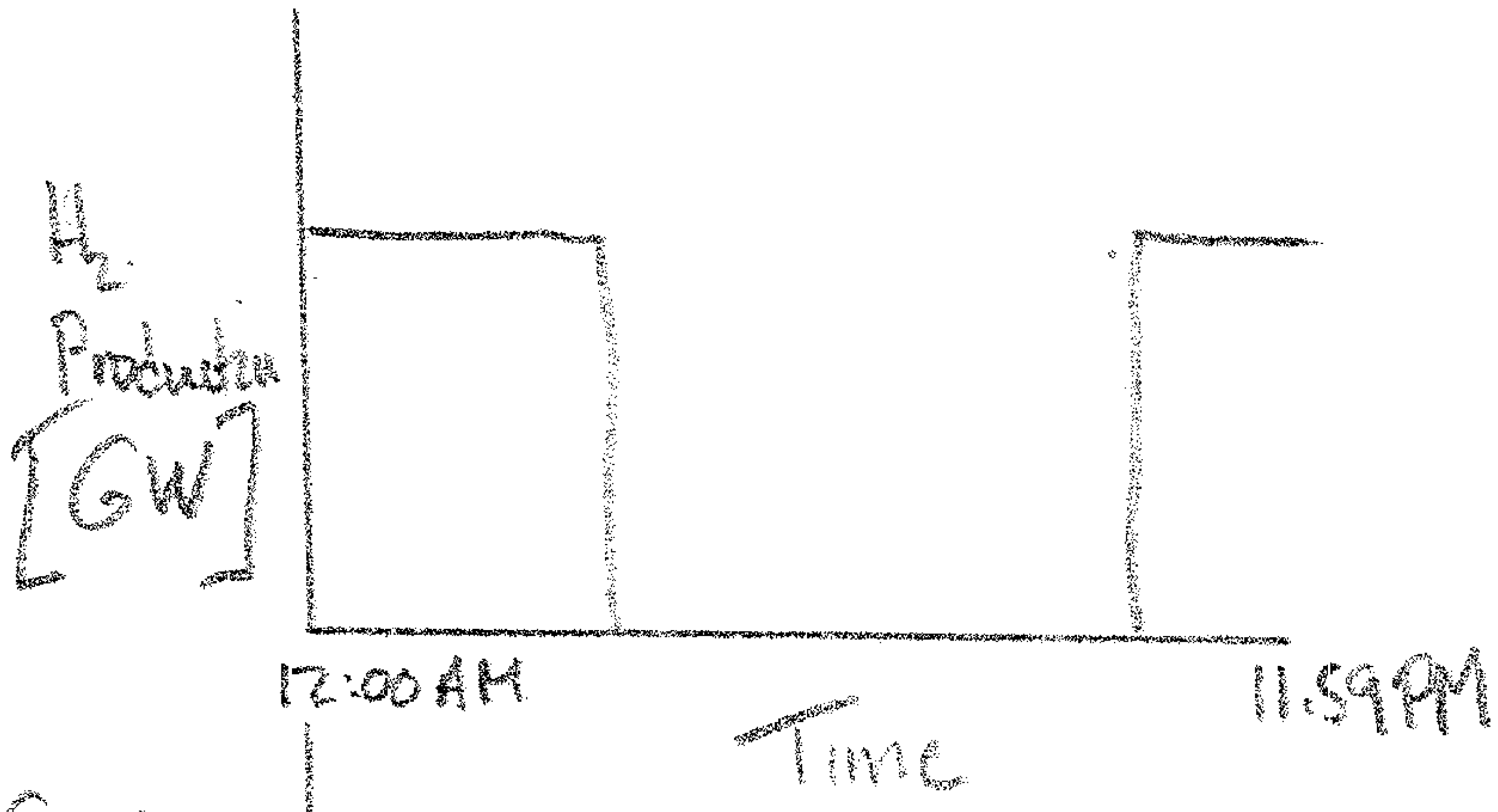


Figure 5(c) Hydrogen Production Schedule

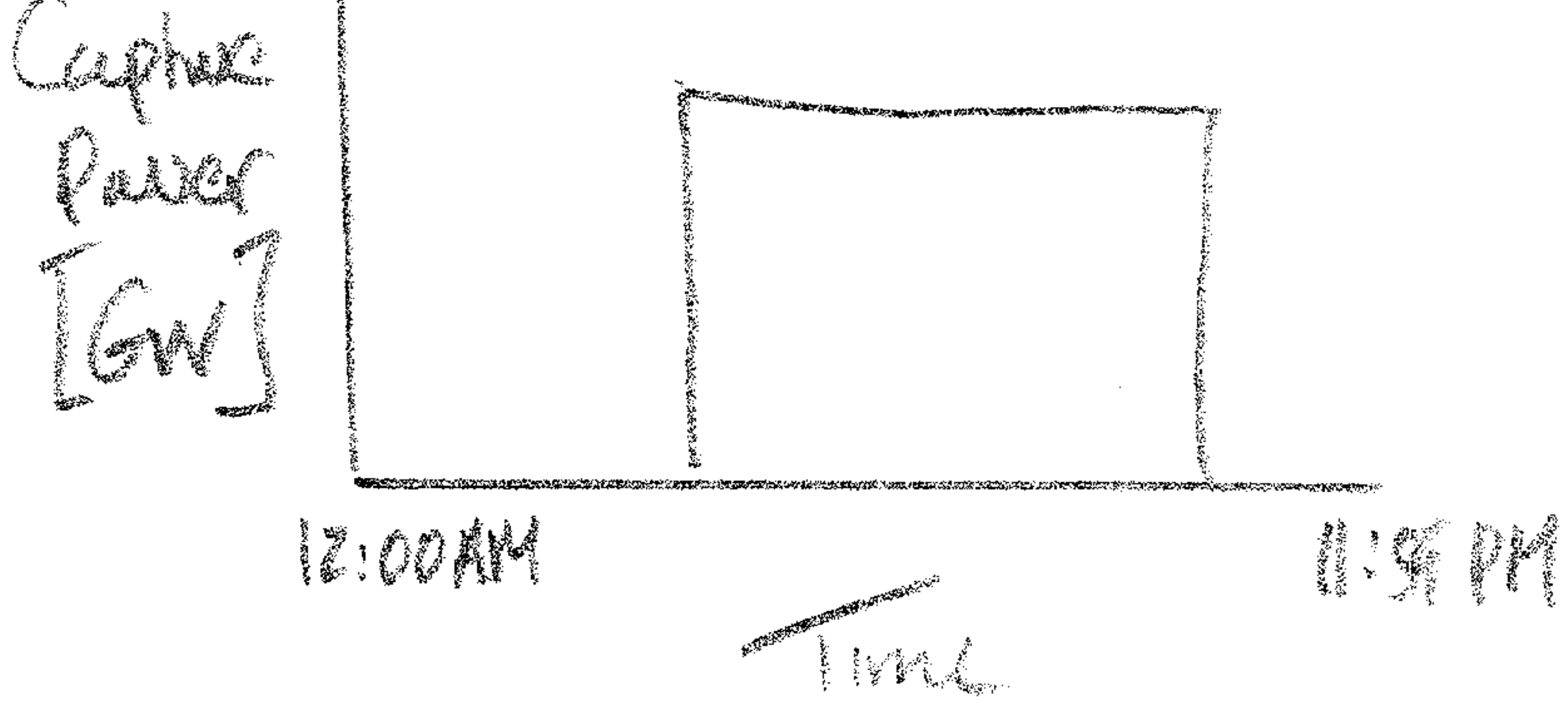


Figure 5(d) Capture Power Sold to Grid

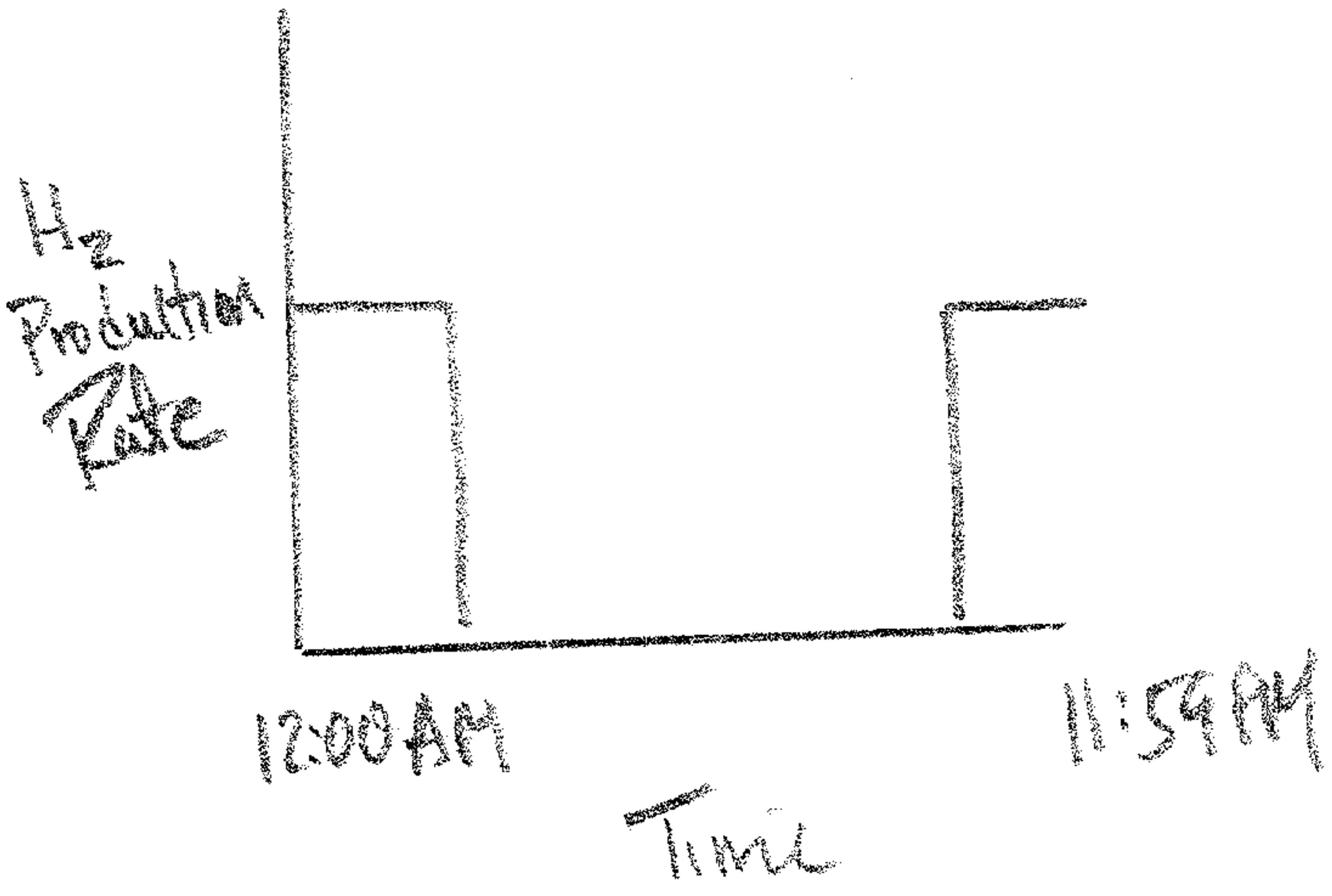


Figure 5(e): Hydrogen Production Schedule fueling fleets at night

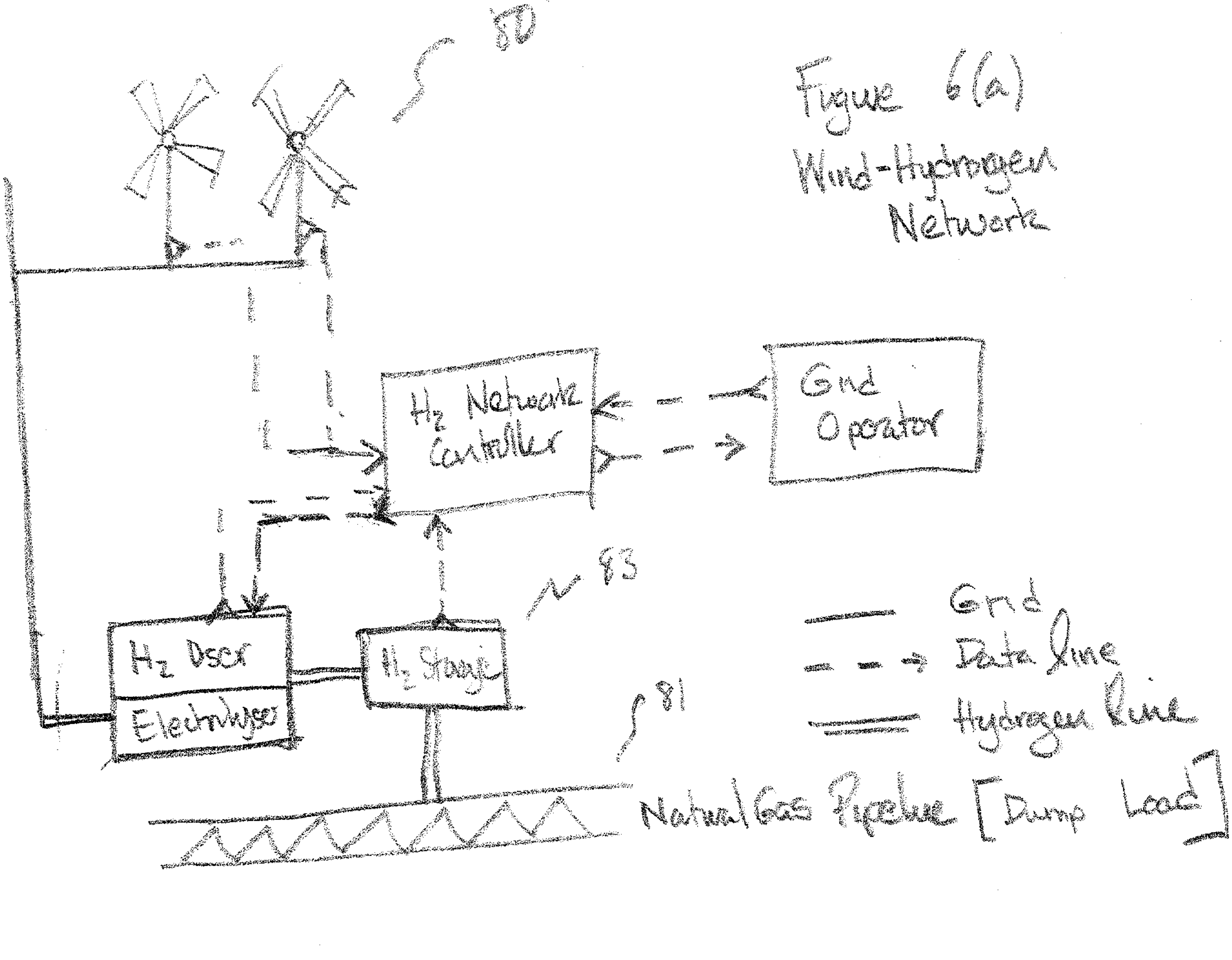


Figure 6(a) Wind-Hydrogen Network

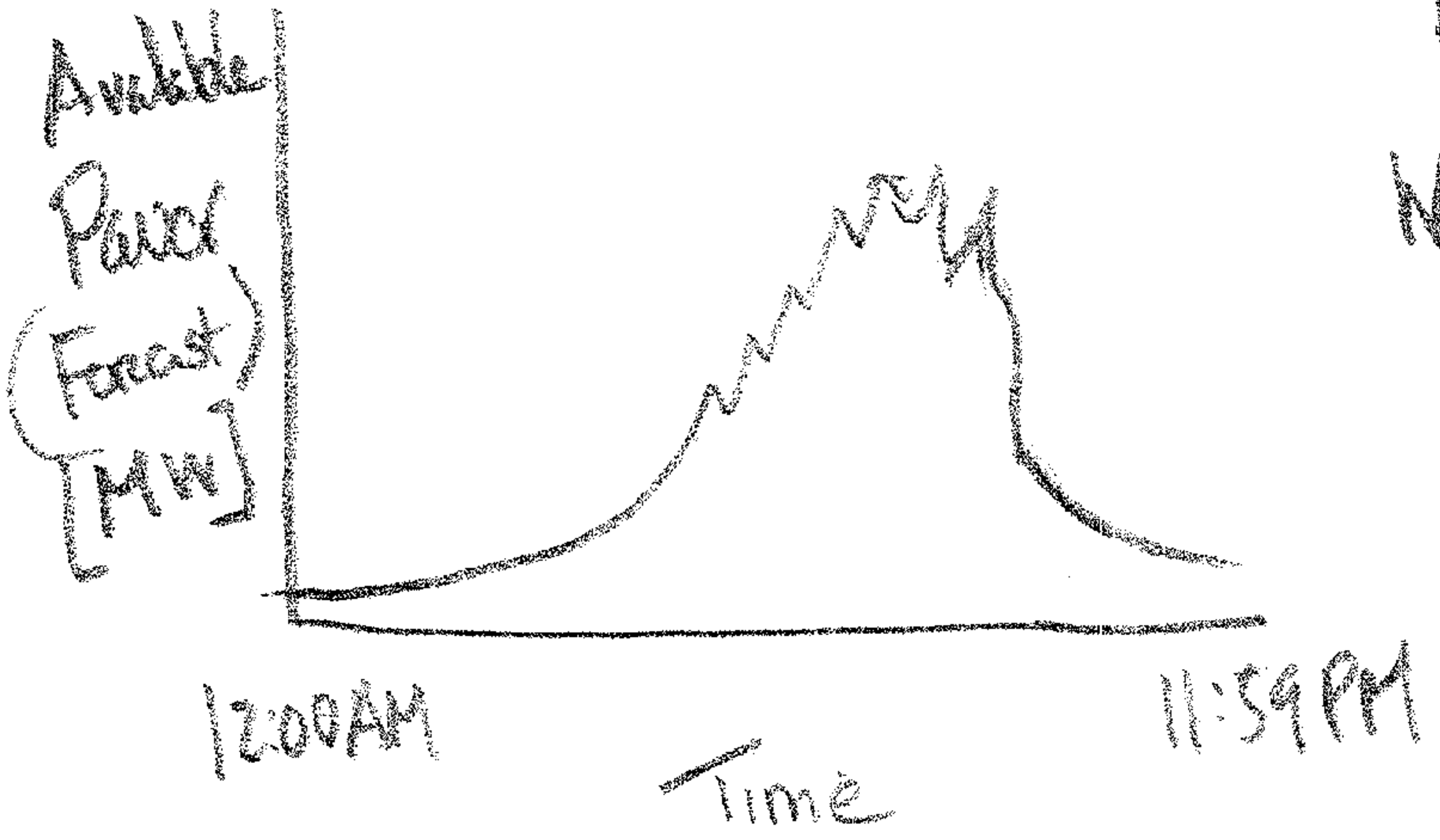


Figure 6(b)
Wind Power Availability Profile

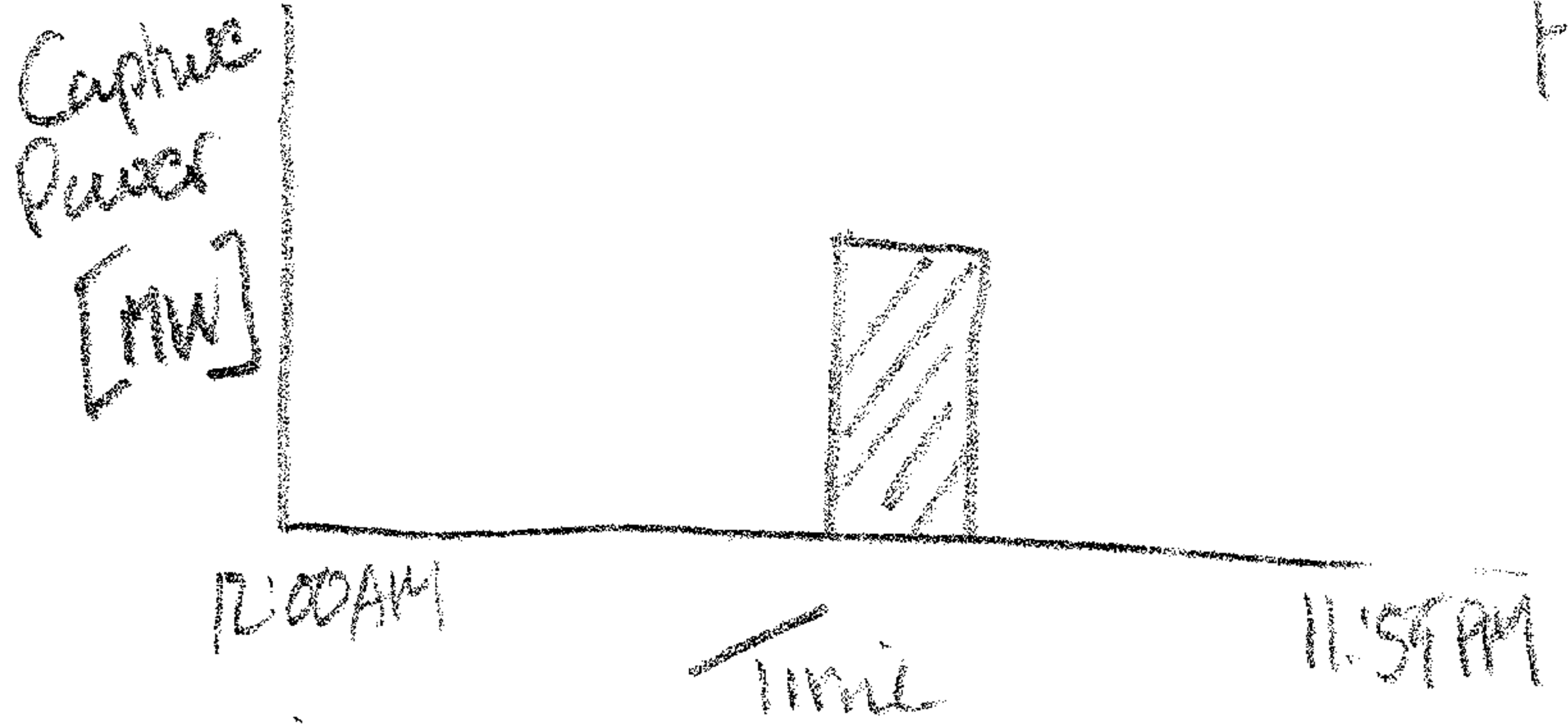


Figure 6(c)
Capture Power Sale to Grid

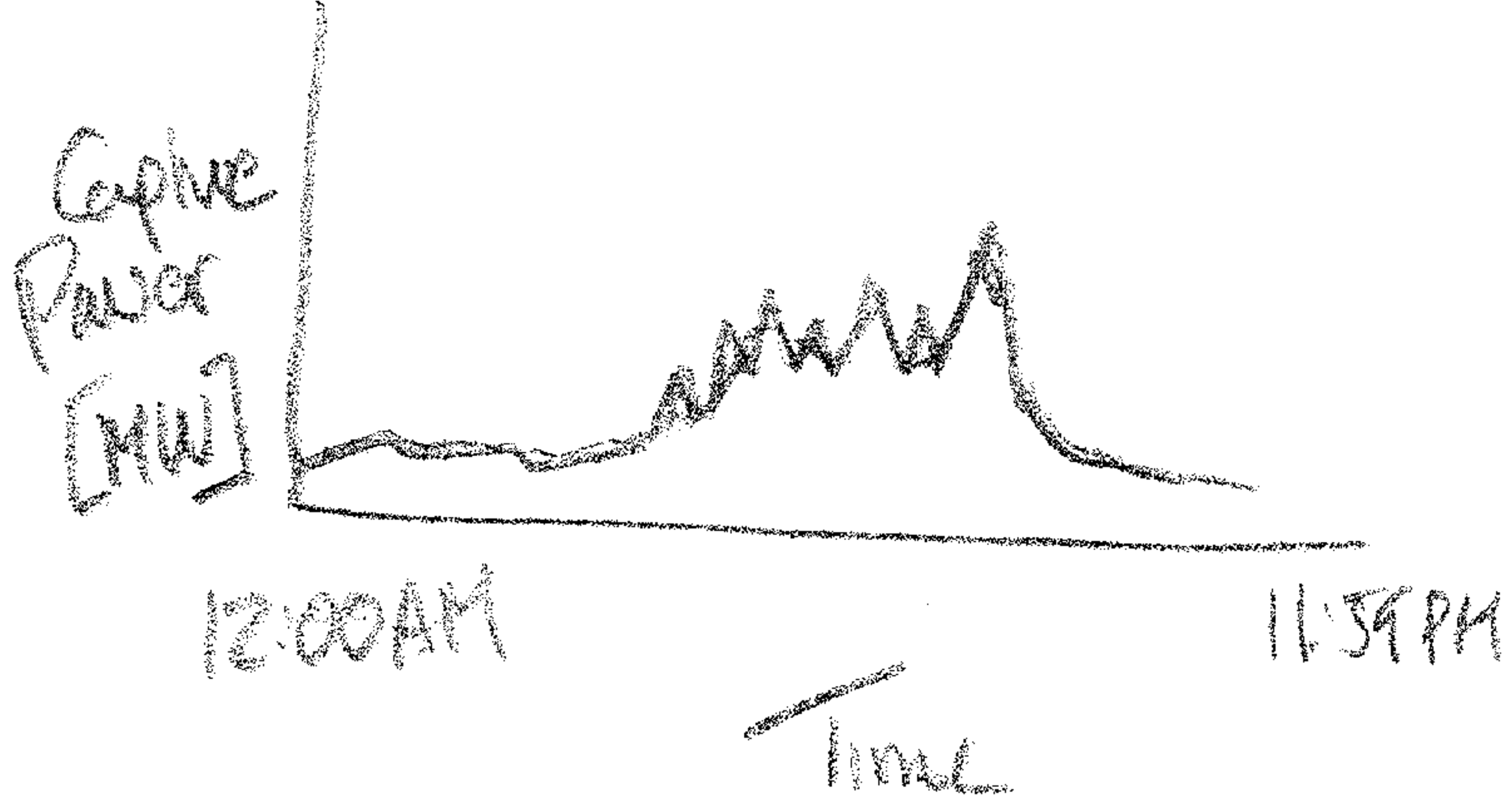


Figure 6(d)
Capture Power for Hydrogen Production

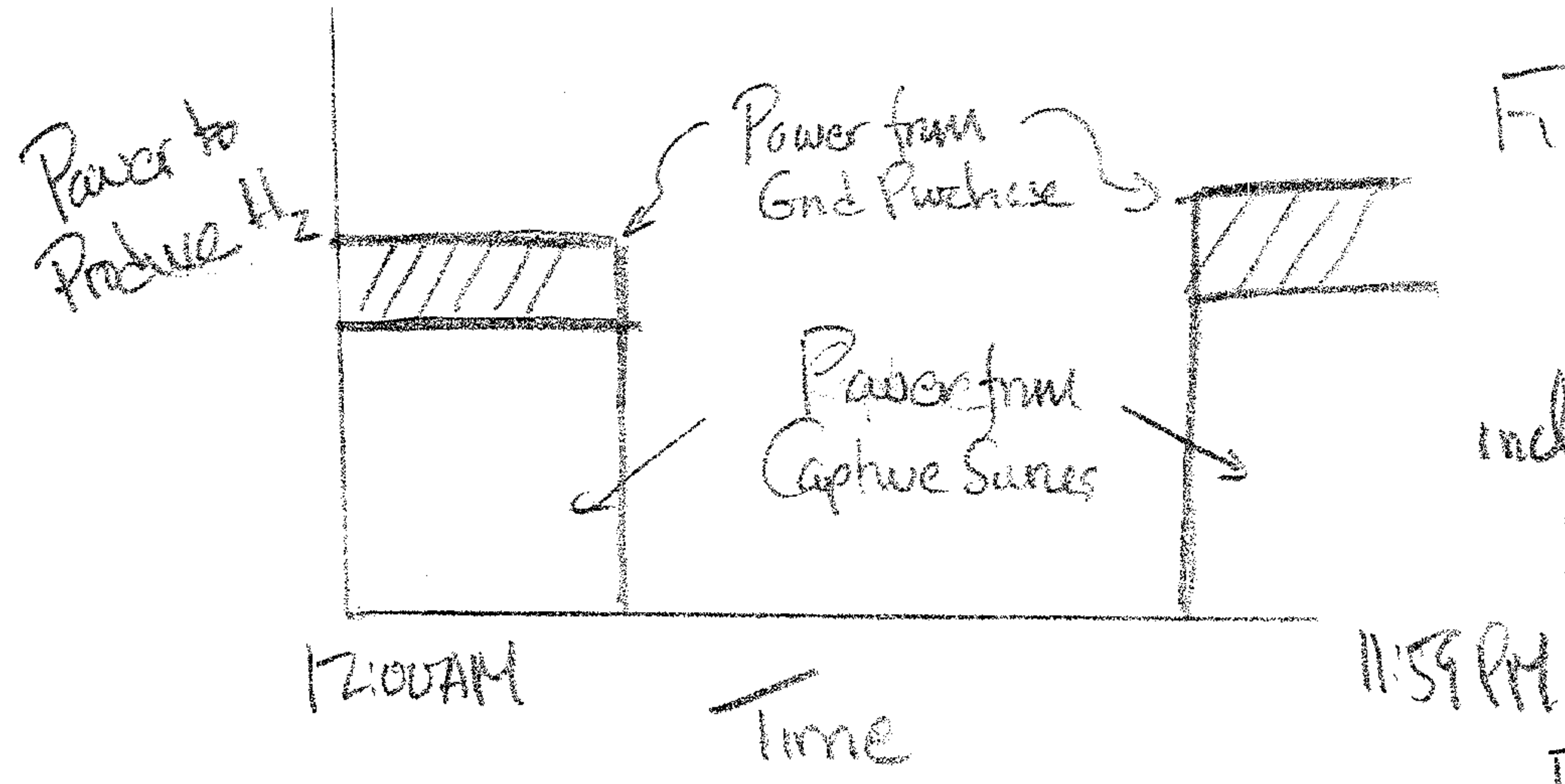
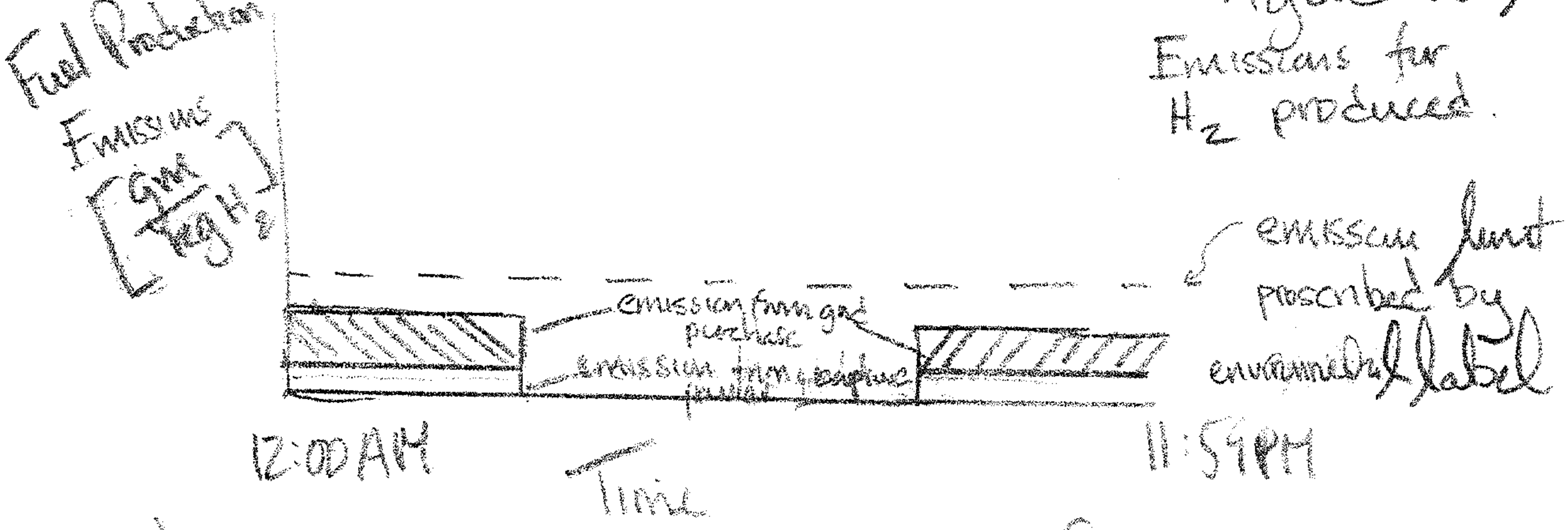


Figure 7(a)

Power Supply for H_2 Production including Purchase from Grid

Figure 7(b)

Emissions for H_2 produced.



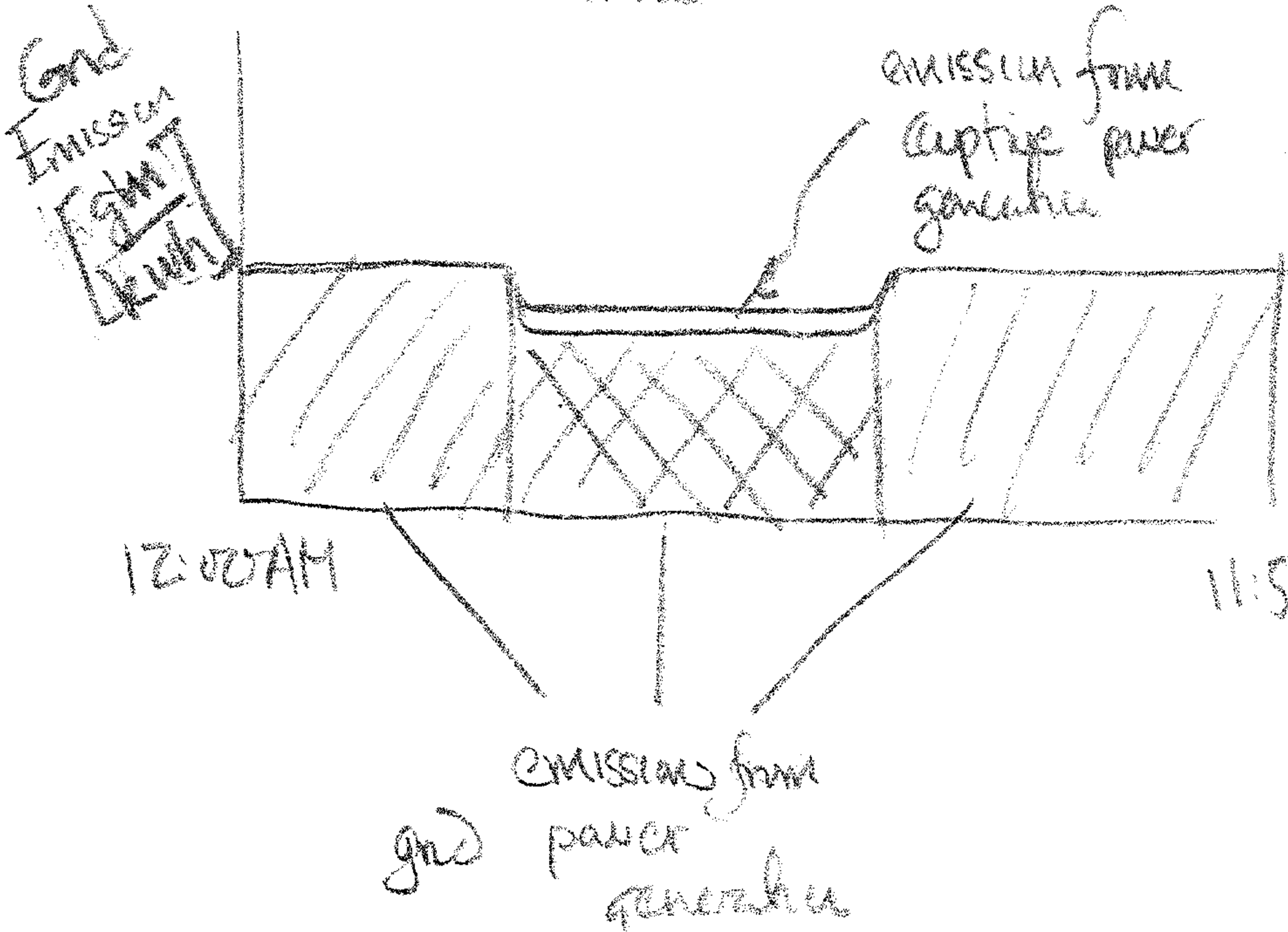


Figure 7(c)

Specific Emission Rate for Grid Electricity

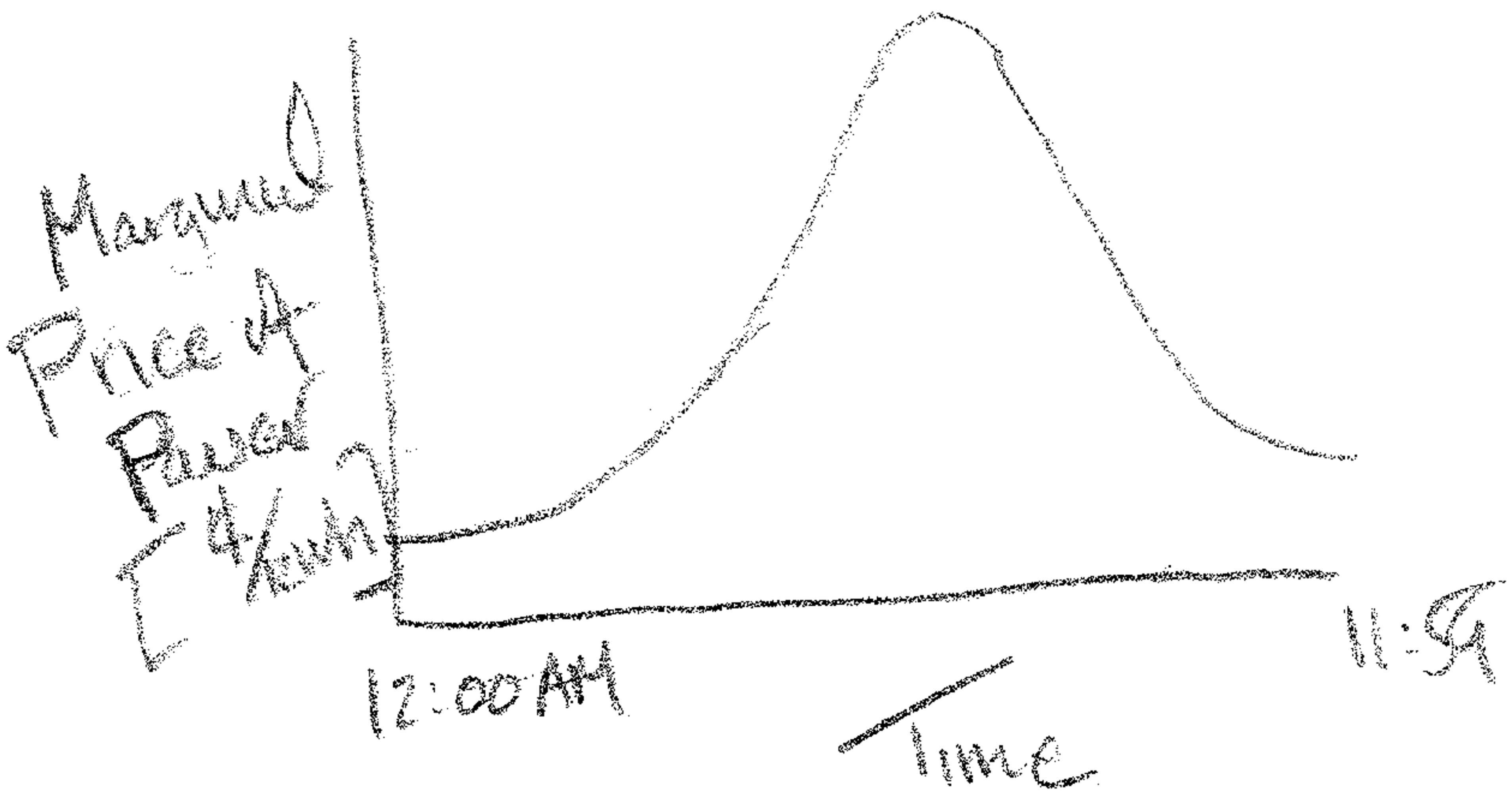


Figure 8(a)

Marginal Price Of Power on Public Grid

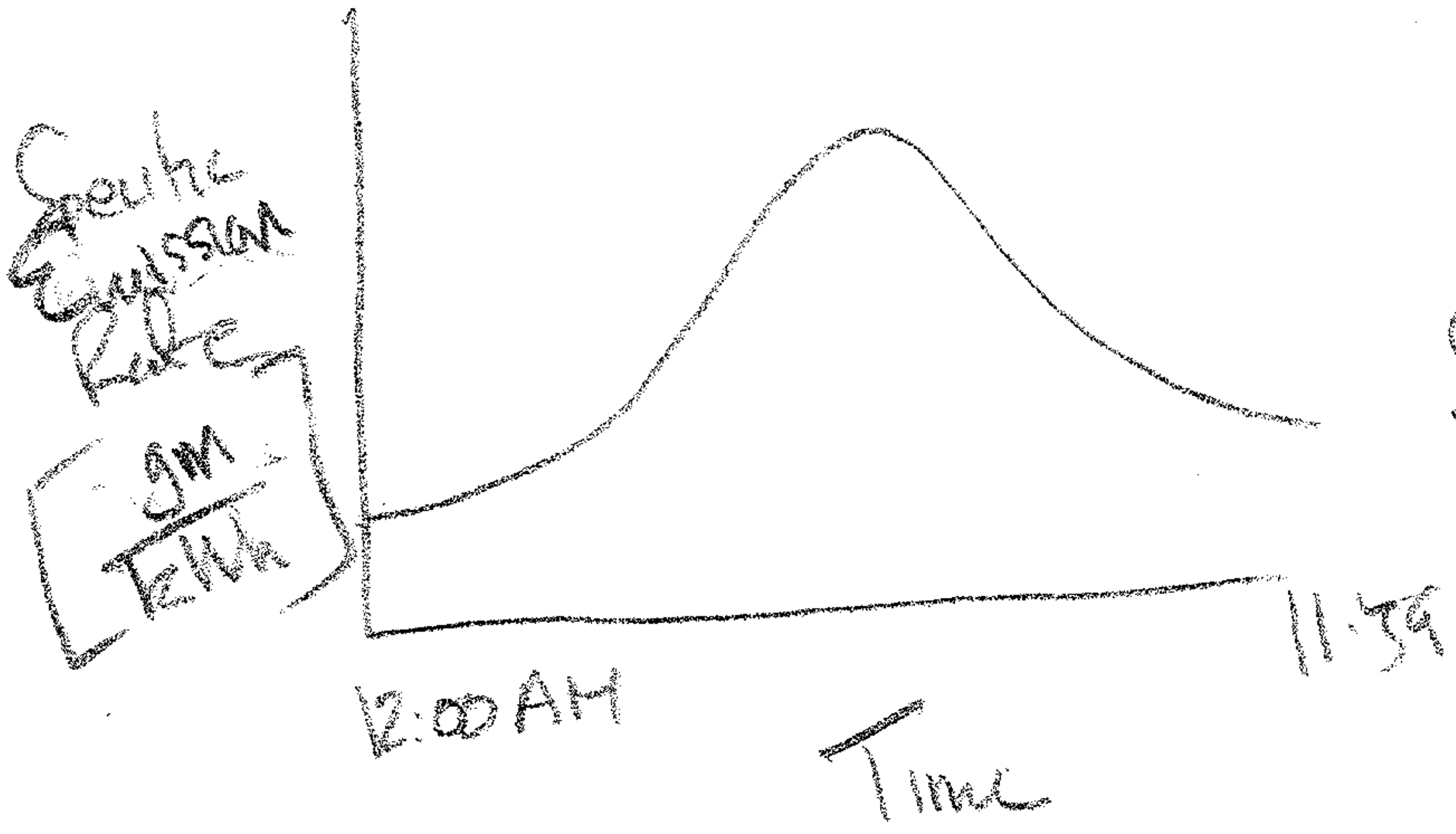


Figure 8(b)

Specific Emission Rate for Public Grid

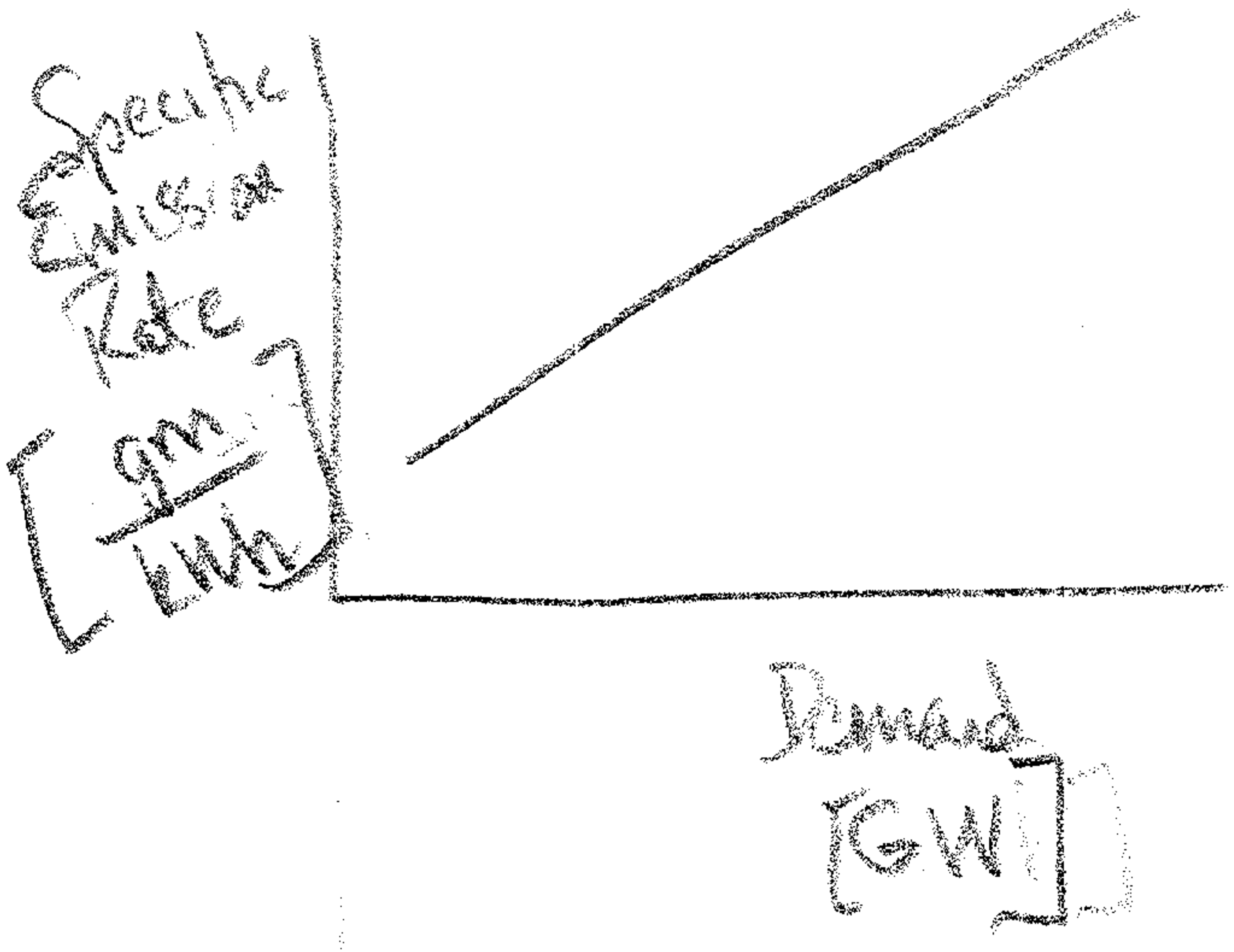


Figure 8(c)

Specific Emission Rate for Public Grid

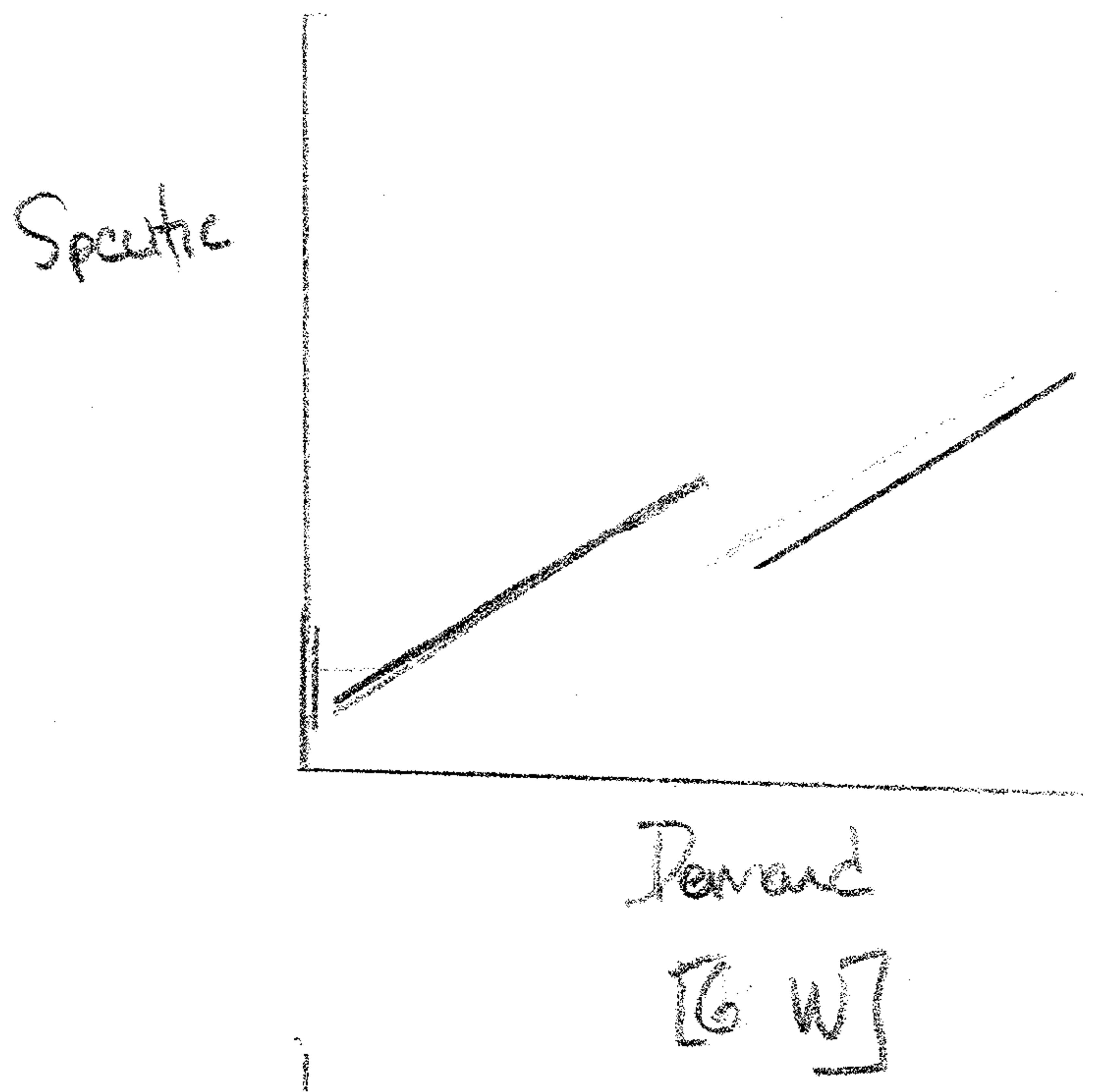


Figure 8(d)

Specific Emission Rate for Public Grid (including Captive Power)

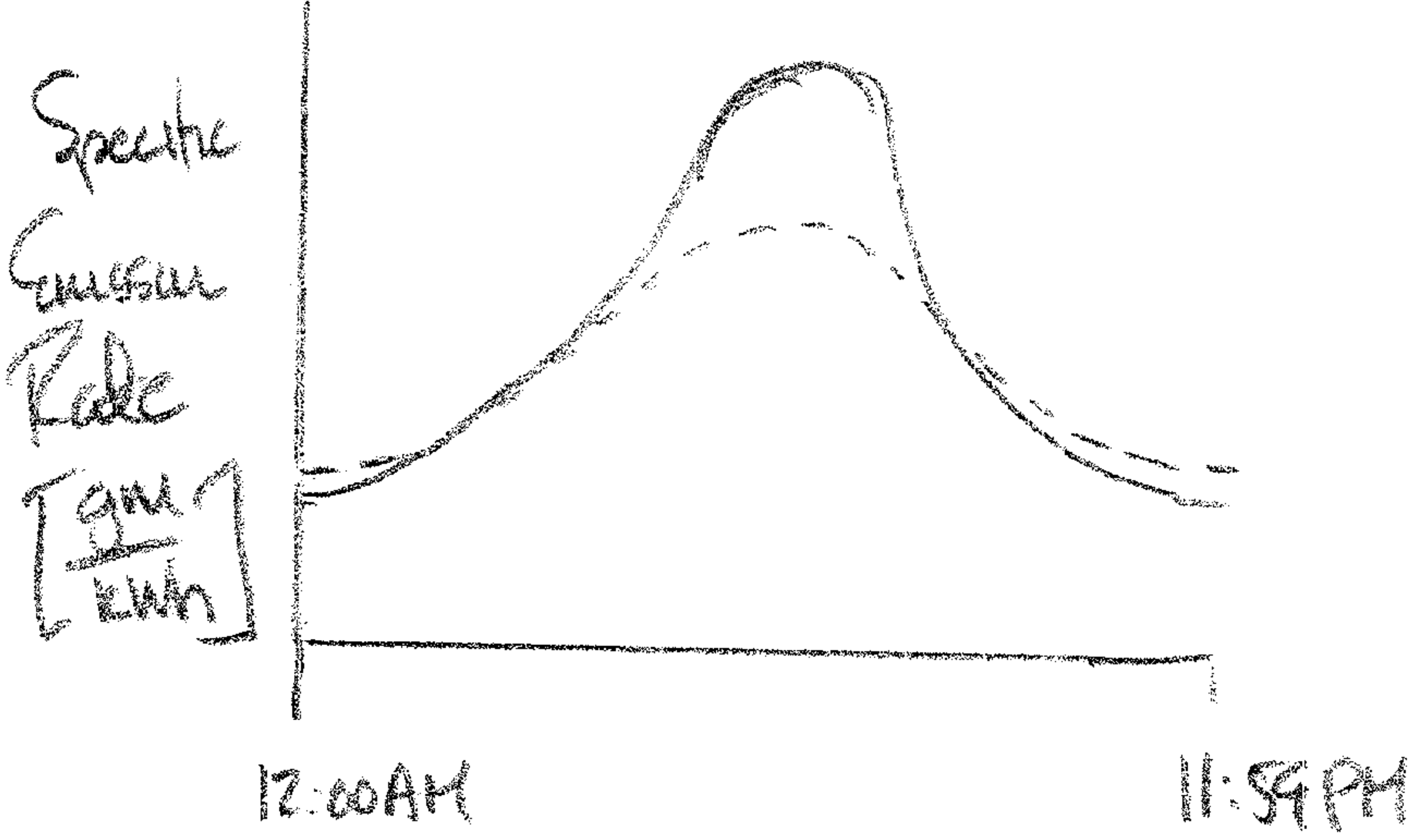
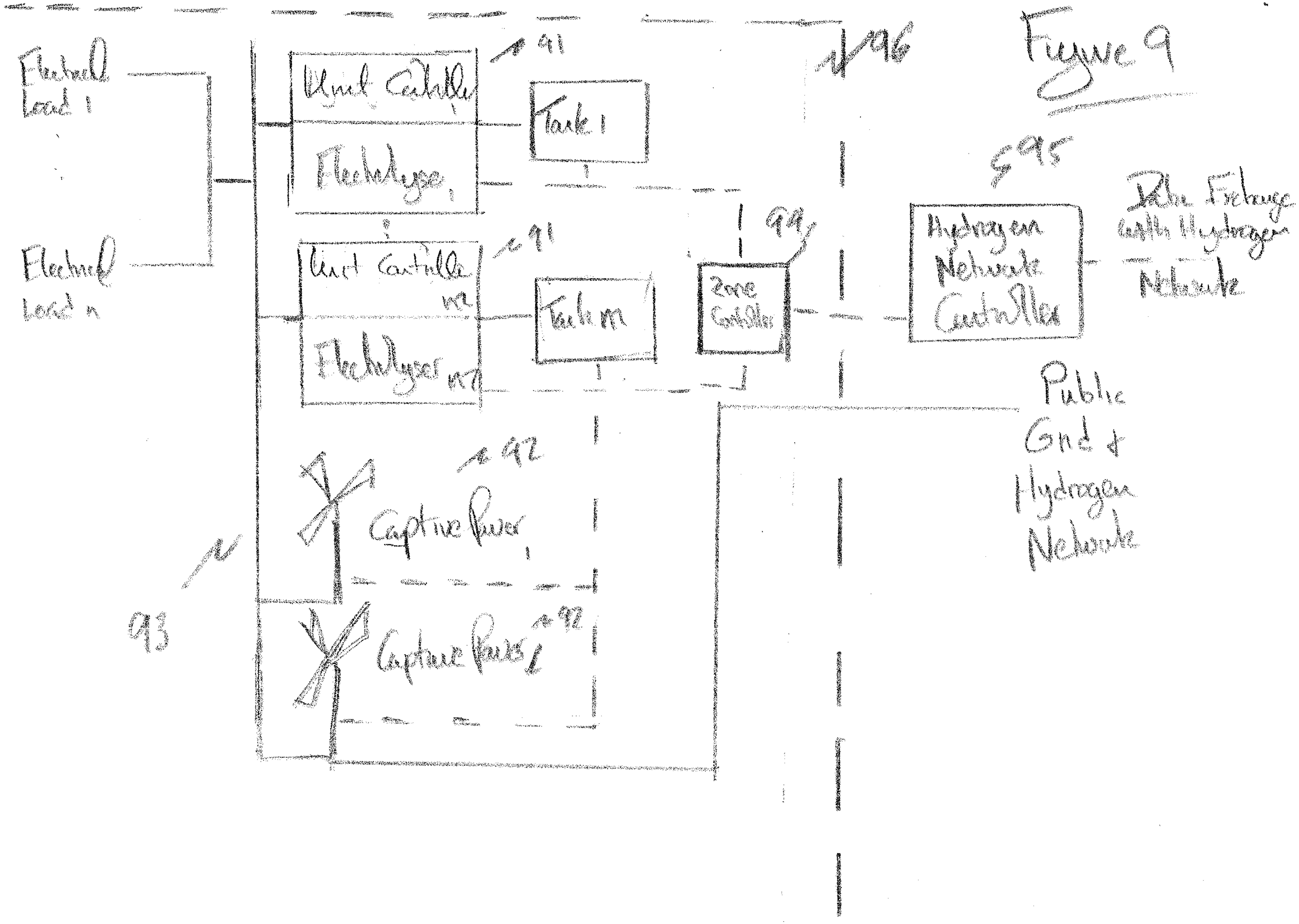


Figure 8(e)

Specific Emission Rate for Public Grid (including Captive Power)

Figure 9


Electrical Load 1
Electrical Load n
91
Unit Controller 1
Electrolyser 1
Tank 1
91
Unit Controller m
Electrolyser m
Tank m
92
Captive Power 1
92
Captive Power L
93
94
Zone Controller
96
95
Hydrogen Network Controller
Data Exchange with Hydrogen Network
Public Grid & Hydrogen Network

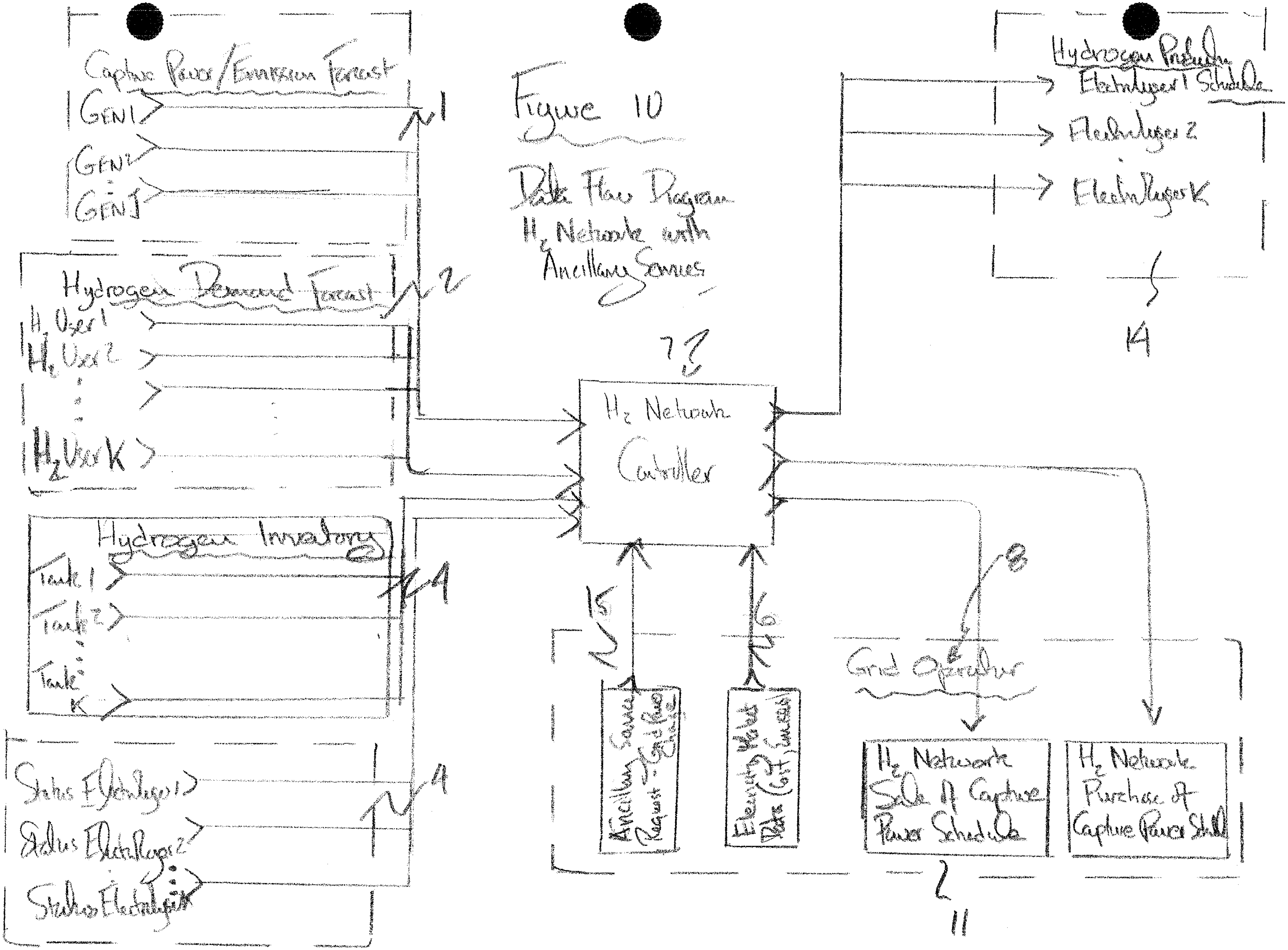
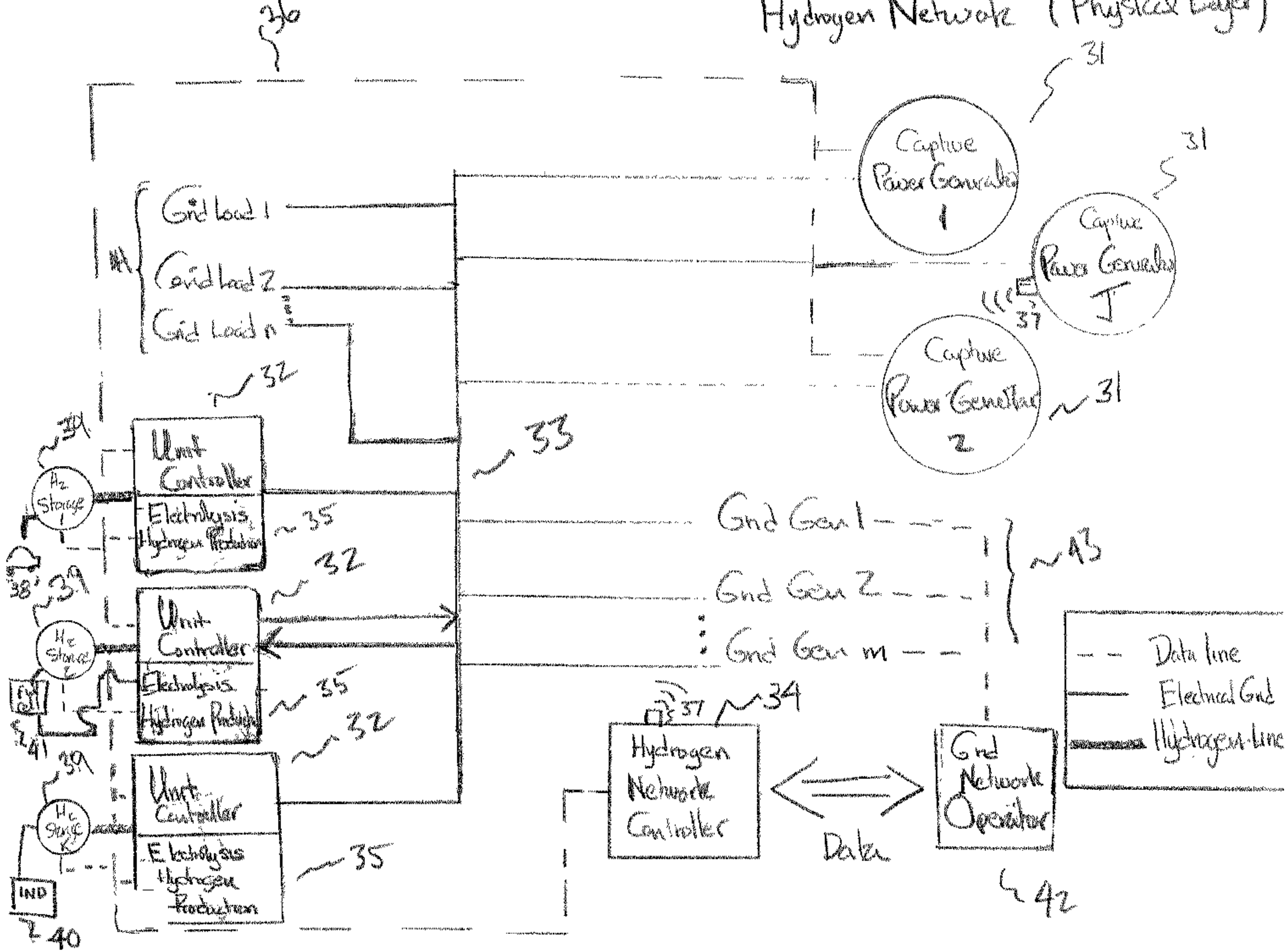


Figure 10

Data Flow Diagram
H_2 Network with
Ancillary Services



Hydrogen Network (Physical Layer)