FEASIBILITY OF DIESEL-ELECTRIC HYBRID DRIVES FOR COMBINE HARVESTERS

by

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ABSTRACT

Efficiency and technology are increasingly important selling points for combine harvesters. Diesel-electric hybrid drives have taken hold in the construction equipment industry, and are providing marketable efficiency benefits for some heavy equipment customers. This thesis explores the technical and economic feasibility of utilizing diesel-electric hybrid drives on AGCO combine harvesters.

To determine the technical feasibility of utilizing diesel-electric hybrid drives on AGCO combine harvesters, a search was conducted for prior literature relating to the use of electric drives on other heavy, off-highway equipment. This information, coupled with data provided by experts in the field, was used to determine if electric drives could fulfill the unique requirements of combine harvesters, and be practically utilized for this application.

To determine the economic feasibility of utilizing diesel-electric hybrid drives on AGCO combine harvesters, an optimization model was constructed to seek out the most economically viable configuration of electric drives for this application. The model takes in to consideration the different use-cases in which this equipment is expected to perform, as well as the component costs and operating efficiencies of both the drives in place currently and the proposed electric drives. The outcome of the model was then utilized to compare the best-case configuration to the minimum requirement for economic feasibility.

The technical feasibility assessment conducted for this thesis led to the conclusion that it would be technically feasible to utilize electric drives on a combine harvester. There are commercially available electric drive components which are suitable for use in the environment that this equipment is expected to operate in, and a prototype combine harvester having electric drives has previously been constructed.

The economic feasibility assessment conducted for this thesis revealed that it is not economically feasible to utilize electric drives on AGCO combine harvesters at this time. Under the current circumstances, the most economically viable configuration would take nearly twice the machine's usable operating life to provide a benefit to a customer from fuel savings. Sensitivity analysis revealed that significant changes in the price of fuel or electric drive components would be necessary to change the outcome of this study.

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CHAPTER I: INTRODUCTION

The first combine harvester was patented in 1834, and pulled by a team of horses or mules (Cornways 2012). Since that first combine harvester, these machines have been constantly evolving into the high-tech pieces of equipment that can now steer themselves through the field, harvesting at a rate likely unfathomable to those who first conceived the concept. Combine harvester development is far from complete, and if further improvements are made strategically, advances in harvest efficiency and technology could generate a competitive edge in the market for a leading manufacturer.

The typical combine harvester on the market today couples a diesel engine with various mechanical and hydraulic drives to cut and gather the crop standing in the field; thresh and separate the grain from the other crop material; discharge the material other than grain; clean the grain; and then convey the cleaned grain in to a cart or truck for transport out of the field. A compilation of sub-systems is utilized to accomplish each one of these tasks; and each sub-system typically has its own unique set of drives to provide the power necessary to accomplish the function. Figure 1.1 below shows a cutaway view of one configuration of combine harvester, and begins to illustrate the quantity of moving parts and systems in a typical machine. Additionally, combine harvesters are used in many different crop conditions all around the globe, each of which provides a unique set of requirements for individual drives on the machine.

Figure 1.1: AGCO Fendt Combine Cutaway View

(AGCO Corporation 2012)

This thesis will explore the economic and technical feasibility of converting the mechanical or hydraulic drives on AGCO's present combine harvesters to electric drives. To begin to understand the feasibility of undertaking a change like this, it must first be understood whether utilization of electric drives on a combine harvester of today's capabilities is technically possible or desirable. It must be established whether the electric components required to power the subsystems exist or could be built in a form practical for use on a combine harvester; and if the technical features of these components would be desirable for this application. After technical feasibility is established, economic feasibility can be explored. Economic feasibility must be explored from two different perspectives—from the customers', and AGCO's point of view. An economically viable configuration will be examined through analyzing the construction costs and operating efficiency differences between the proposed electric drives and the current drives used on AGCO's combine harvesters. If the electric machine configuration proves to hold an economic advantage over the current configuration, it must be determined if AGCO can profitably implement the design, manufacturing, and product support changes necessary to successfully launch and market the product, and ultimately if the project should logically be pursued.

CHAPTER II: LITERATURE REVIEW

The literature available concerning the commercial installation of electric drives on combine harvesters is fairly limited. There has been one university in Germany which has built a functional prototype combine having electric drives (B. Bernhard 2003), but the literature is sparse concerning commercial offerings of a major electric drive system on a combine currently available for sale. The only offering found is an optional configuration for the chopper on a Rostselmash combine built in Russia. Rostselmash vaguely touts the electric chopper drive's ability to be easily controlled, but makes no mention of any other benefits in their marketing materials (Rostselmash 2012).

The University of Hohenheim in Germany has built a functional combine prototype having an electric ground drive, and has laid out their strategy for electrically driving the threshing rotor and auxiliary drives. At the time of publication, Bernhard and Schlotter (2003) posited that if electric drives were utilized on a combine harvester, weight and production cost would increase, but controllability and fuel consumption would be improved, reducing operating expenses for the end user.

When considering the installation of electric drives on a combine harvester, there are several pros and cons to consider. In a survey of Austrian agricultural machinery manufacturers, a list of major advantages and disadvantages to installing electrical drives was compiled. The list of advantages was as follows: controllability, easy torque and speed measurement, possibility for fault finding, easy distribution of power, high efficiency, overload capability, and low noise level. The list of disadvantages was as follows: High mass, (large) space requirements, cost efficient standard components not currently available, (low) robustness, safety requirements, interface problems, and (lack of) storage technology. The conductors of the survey also posit that,

> *"Electric drives will gain acceptance in the future. But a total substitution of mechanic or hydraulic drives is not expected. The time frame for triggering market penetration will be 5 to 10 years. Standardization is seen as a key issue for successful implementation. Research and engineering has to focus on the development of robust, customized but cost efficient components" (Jürgen Karner 2011).*

These works were found to be the most pertinent in relation to the installation of electric drives on combine harvesters. No works were found that spoke in any specificity to the economic feasibility of these systems.

2.1 Other Off-Highway Hybrids

Although there is little work concerning electric drives on combine harvesters, there is a considerable amount available for construction equipment, such as bulldozers and loaders. Although the use-cases and expected service lifetimes are much different for these machines, the harsh operating environment can be similar in terms of dust exposure, temperature extremes, and a nearly continuous duty-cycle. The first, and most prevalent, example of a piece of large, diesel-electric hybrid construction equipment was the Caterpillar D7E track bulldozer, illustrated in Figure 2.1 below (Korrane 2009). Caterpillar touts that the D7E is 25 percent more efficient than its comparable standard model; and, though it costs 20 percent more at a suggested retail price of $600,000, it can make up the cost differential in three years of use. Caterpillar has been successfully marketing the D7E since 2009 (Hampton 2009).

Figure 2.1: Caterpillar D7E Electric Drive Overview

(Caterpillar 2013)

CHAPTER III: CONCEPTUAL FRAMEWORK

To determine whether pursuing a project to convert existing combine drives to electric drives is worthwhile, we must first understand what criteria must be met to make pursuing the project feasible. According to Dr. Vincent Amanor-Boadu (2003), "Feasibility assessment is the disciplined and documented process of thinking through an idea from its logical beginning to its logical end to determine its practical viability potential, given the realities of the environment in which it is going to be implemented" (p. 1).

In this case, the logical beginning of the converting to electric drives on combine harvesters lies in assessing the technical, or engineering, feasibility of doing such. It must first be understood what the power requirements are for each drive and function, and whether hardware exists or could be made which would fulfill these needs on a mobile machine practically. It must also be understood what different use-case scenarios the combine would be expected to work in to insure the electric generation capacity and motors on board could fulfill all of the requirements. From a technical perspective, the other factor which needs to be considered is what impact changing to electric drives would have on the efficiency or functionality of each area of the machine. In other words, how the change would affect the operating characteristics of the combine harvester, either through altering the conversion of power to work (fuel efficiency) or impacting the harvest performance (grain loss and throughput capability). For the purpose of this study, it will be assumed that converting to electric drives will have a negligible impact on harvest performance; seeing that only the power source for the drives would be changed. Therefore, focus will be devoted to examining the impacts to power conversion, or efficiency. In short, to determine the technical feasibility, we need to answer the questions “Will it work?” and “Can it be built?”.

Once technical feasibility is established, the decision whether to pursue a project to convert to electric drives comes down to economic feasibility. It must be understood what the cost impact of converting the specified drives would be, and whether there is value generated for customers by changing drive types. Whether value is generated for customers can be determined by examining the expected price change in the combine to the expected monetary gains over the life of the machine due to productivity or efficiency improvements from converting the drives. In other words, it should be determined if the investment that a customer would make in a combine with electric drives could have a higher net present value than an investment made in a combine with traditional drives. Once the presence of added customer value (or marketability) is established, the remaining point to examine is whether pursuing a combine drive conversion project could hold value for AGCO’s shareholders. The net present value of undergoing this engineering project relative to other alternatives needs to be considered to make the best use of AGCO’s limited resources.

3.1 Assessing Technical Feasibility

To assess the technical feasibility of converting to electric drives on AGCO’s combine harvester, a search for prior literature will be conducted to determine if a combine harvester with electric drives has ever been constructed, or if mobile equipment having similar requirements has ever been constructed with electric drives. Data will also be compiled for the power requirements for each drive in various use-case scenarios for the

AGCO combine harvester, and a search will be conducted for electric components which would be candidates for power generation, motors, and controls to fulfill those requirements. If off-the-shelf components are not found to exist that fit the desired form-factor, discussions with component manufacturers will be held to establish the technical feasibility of constructing such devices.

To further analyze technical feasibility, data will be collected on the capabilities and efficiencies of electric, hydraulic, and mechanical drives. This data will be used to compare features such as controllability, maintenance requirements, durability, torque generation capabilities, size, and weight. Combine harvesters are used in a uniquely challenging environment, subject to extraordinary levels of dust, vibration, and environmental extremes. To establish technical feasibility, the robustness of the components required for the electric drives must be explored relative to the current systems used today. Soil compaction is a growing concern among combine harvester customers, so the weight of the electric drive components relative to the components in place will also be important. The physical size of the components will also need to be explored, as the overall size of the combine harvester cannot grow appreciably due to size restrictions for shipping and road transport.

Another aspect of technical feasibility which will need to be established is the manufacturability of a combine harvester having electric drives. A search for prior literature will be conducted to see if anyone has manufactured a modern combine harvester with electric drives, or if any similar piece of machinery has been assembled with electric drives. It would be reasonable to conclude that if machines with similar characteristics have been constructed with electric drives in the past, manufacturability of these systems is not a problem.

3.2 Assessing Economic Feasibility

After technical feasibility is established, the economic feasibility of a combine harvester with electric drives can be determined, and it can be determined which configuration could be most feasible. This economic exploration will answer the question “Should we?”, and will uncover whether a machine with electric drives can hold economic benefit to a customer, and if that economic benefit for the customer could be leveraged to generate an economic benefit for AGCO.

One of the challenges in determining the most feasible configuration of combine harvester drives to convert to electric is the broad range of conditions that these machines are used in. For example, when harvesting wheat, there is generally a relatively low power demand for the header drive, yet a rather high power demand for the threshing rotor drive. On the contrary, when harvesting corn, there is generally a relatively high power demand for the header drive, and a low power demand for the threshing rotor drive. The challenge will come in finding a configuration where the system is adequately sized to handle all conditions, but where there is not undue cost added to an area of the machine where the capabilities of a large electric drive would be underutilized. In other words, if cost is added by converting to electric drives, the electric drive should see a relatively high duty cycle for use, rather than only being utilized to its full capabilities under very specific conditions. Proper implementation in this regard would be critical for customer attraction and retention, because, in addition to actually providing an economic benefit, it is estimated that it will also be important that the customer perceive that the electric drives are being extensively utilized. To insure the configurations explored are neither over nor under-utilized, a matrix of use-case scenarios will be established as an input to an optimization model constructed for this assessment. This matrix will list a broad range of conditions where the combine harvester will be expected to be used, and the power required for each drive on the machine under each scenario. This will allow the optimization model to eliminate any configurations that don't meet the minimum requirement for a listed scenario, and will also allow the level of electric drive utilization for different configurations to be explored.

It is hypothesized that a combine harvester utilizing electric drives will cost more to build than a traditional combine harvester, but that fuel efficiency gains will eventually offset the additional purchase expense, and pay dividends to the customer through fuel savings, thus lowering the total cost of ownership. To test this hypothesis, an optimization model will be constructed to explore all technically possible drive configurations, seeking out the configuration that offers the lowest payback period, or alternative configurations that would provide a reasonable payback period. The payback period (in hours of harvest operation) will be estimated by taking the retail cost of the electric drive(s) added, minus the retail cost of the mechanical or hydraulic drive(s) replaced, divided by the estimated fuel savings per hour. The estimated fuel savings per hour can be calculated through taking the brake-specific fuel consumption of the diesel engine (a figure typically given in pounds of diesel fuel per horsepower-hour), multiplied by the efficiency gain of the new system relative to the old system, expressed in horsepower. This equation will result in pounds of fuel saved per hour of machine operation, which can then be translated in to gallons saved per hour, and dollars saved per hour given the price of diesel fuel. Using this information, the estimated number of operating hours required to break even on the investment made in a combine harvester having electric drives, versus one without can be figured. In addition, sensitivity analysis will be performed for different fuel and electric component prices, as well as differing levels of electric drive system efficiency.

CHAPTER IV: EMPIRICAL METHODS AND DATA

This chapter will explain the methods used in this study to assess the technical and economic feasibility of converting to electric drives on combine harvesters. The calculations, figures, and assumptions used will be shared and discussed; building the foundation upon which the conclusions for this thesis were drawn.

4.1 Assessing Technical Feasibility

To assess the technical feasibility of converting the existing drives on AGCO's combine harvester to electric drives, a literature review was performed to look for any prior use of this technology in off-highway equipment. The paramount example of this technology's use in off-highway equipment is the Caterpillar D7E bulldozer. While bulldozers and combine harvesters are very different pieces of equipment, there are many similarities to the environments in which they are required to operate. The operating environment for both machines can be very dusty, with hot and cold temperature extremes, and they are both expected to operate under nearly continuous duty-cycles. Due to these similarities in operating environments, and similarities in the size of the machines, a comparison was drawn between these two applications to suggest that if electric drives are technically feasible for one, they could reasonably be considered technically feasible for the other.

4.2 Assessing Economic Feasibility

To aid in the assessment of the economic feasibility of converting the existing drives on AGCO's combine harvester to electric drives, an optimization model was constructed. The goal of constructing this model was to uncover the most economically feasible configuration of electric drives on the combine, which is to say the machine configuration which would provide the most economic benefit to a customer over the life of the machine. The effective life of the machine is established at 3,000 harvesting hours. If there is no configuration possible which would generate an economic benefit for the customer within this time period, then the project is deemed not economically feasible at this time. Further, it would be desirable if an economic benefit could be established beyond the machine's half-life, or 1,500 harvesting hours. This would allow for 1,500 hours of additional machine operation during which an economic benefit could be generated for the customer, rather than having the investment in electric drives break-even just as the machine wears out. Expressed in other terms, over the whole life of the machine, this would allow the customer to double the initial investment made in the electric drives.

4.2.1 Model Inputs: Use-Case Matrix

The first objective of the optimization model constructed for this project was to establish technically feasible configurations of electric drives for the combine to allow the exploration of the economic feasibility of these configurations. As mentioned previously, combine harvesters are utilized in many different crop and field conditions, each of which brings a unique set of requirements for the drive for each subsystem on the machine. To insure that an electric drive configuration deemed to be technically feasible could fulfill the requirements of all crop and field conditions combines are expected to work in today, a use-case scenario matrix was generated. This use-case scenario matrix includes both normal crop and field conditions which cover typical power requirements for each drive, as well as extreme scenarios to insure that the machine would maintain the capability to function similarly to current offerings in wet years or in challenging crop conditions. The typical use-case scenarios were included, and weighted, to allow estimation of operating expense impacts of a specific configuration over the life of a typical machine. Scenario weights were assigned based on the likelihood that a typical AGCO customer would use the machine in this scenario, and how often the condition would be expected to be present. Weight values from zero to one were assigned to each scenario based on an expert's (Robert Matousek, AGCO Research and Development Manager) view of how AGCO's combine harvesters are utilized by customers. The use-case matrix also includes scenarios where the machine is required to unload the grain tank while continuing to harvest. For the purpose of this project, fifteen use-cases were generated:

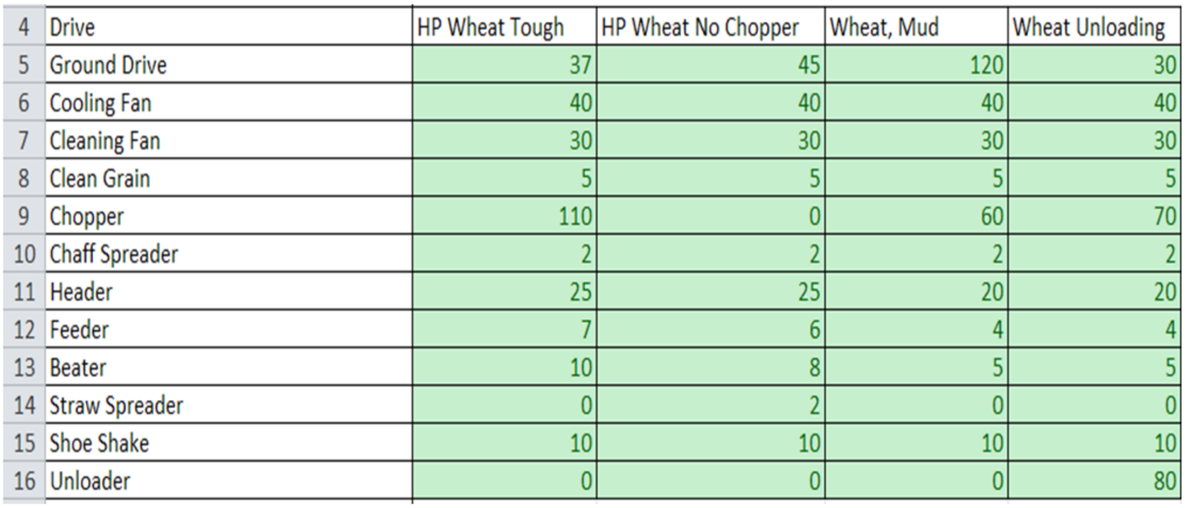
- Wheat, typical
- Wheat, tough
- Wheat, no straw chopper
- Wheat, wet/muddy ground
- Wheat, unloading while harvesting
- Soybeans, typical
- Soybeans, tough/green stem
- Soybeans, no straw chopper
- Soybeans, wet/muddy ground
- Soybeans, unloading while harvesting
- Corn, typical
- Corn, high moisture

- Corn, no straw chopper
- Corn, wet/muddy ground
- Corn, unloading while harvesting

For each of these unique use-case scenarios, the power requirement for each subsystem drive was estimated by an expert in combine design (Robert Matousek, AGCO Research and Development Manager). The power requirement for each of the following drives was estimated, with the remaining system power allocated to the threshing rotor:

- Ground drive
- Cooling fan drive
- Cleaning fan drive
- Clean grain drive
- Straw chopper drive
- Chaff spreader drive
- Header drive
- Feeder drive
- Beater Drive
- Straw spreader drive
- Cleaning shoe drive
- Grain unloader drive

Figure 4.1: Example Use-Case Drive Power Requirements



4	Drive	HP Wheat Tough	HP Wheat No Chopper	Wheat, Mud	Wheat Unloading
5	Ground Drive	37	45	120	30
6	Cooling Fan	40	40	40	40
7	Cleaning Fan	30	30	30	30
8	Clean Grain	5	5	5	5
9	Chopper	110	0	60	70
10	Chaff Spreader	2	2	2	2
11	Header	25	25	20	20
12	Feeder	7	6	4	4
13	Beater	10	8	5	5
14	Straw Spreader	0	2	0	0
15	Shoe Shake	10	10	10	10
16	Unloader	0	0	0	80

Figure 4.1 shows an example of four of the machine use-cases used for this study, and the horsepower requirement for each of the combine's drives in that scenario.

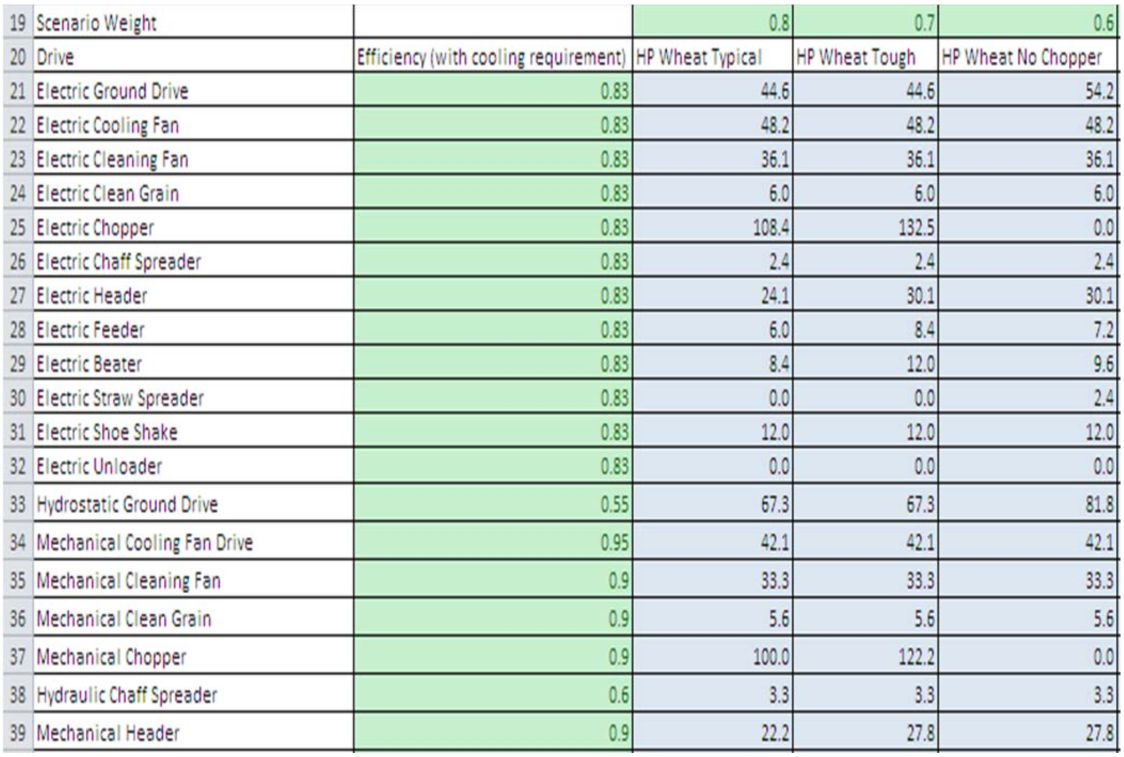
4.2.2 Model Inputs: Generation Capacity and Power Budget

Once the power requirement for each of these drives was established for all of the selected use-cases, options for electric power generation were input. The electric generator options were selected based on three power generation levels that were slated to be AGCO's global standard power generation units at capacities of 60 kW, 140 kW, and 280 kW. A binary table with these generation capacity values was created to enable the selection of a single generator, and establish a balance figure for an electric power budget to be created. Seeing that the power requirements for the subsystem drives were given in horsepower, the electrical generation capacity of these units was also converted to horsepower. The electric power budget in the model insures that the sustained electric power requirement for any of the use-case scenarios does not exceed the power generation capacity of the system. Expressed in other terms:

Electric Power Consumed ≤ Generation Capacity Selected

A critical portion of the power budget in the model is a decision table, used to model different iterations of converting the current subsystem drives in place to electric. By placing a binary value next to the current drive type and the electric configuration of the same drive, the sum product of the electric power consumed for a given drive configuration can be calculated and compared to the total generation capacity available.

Figure 4.2: Example Power Budget Calculated Values

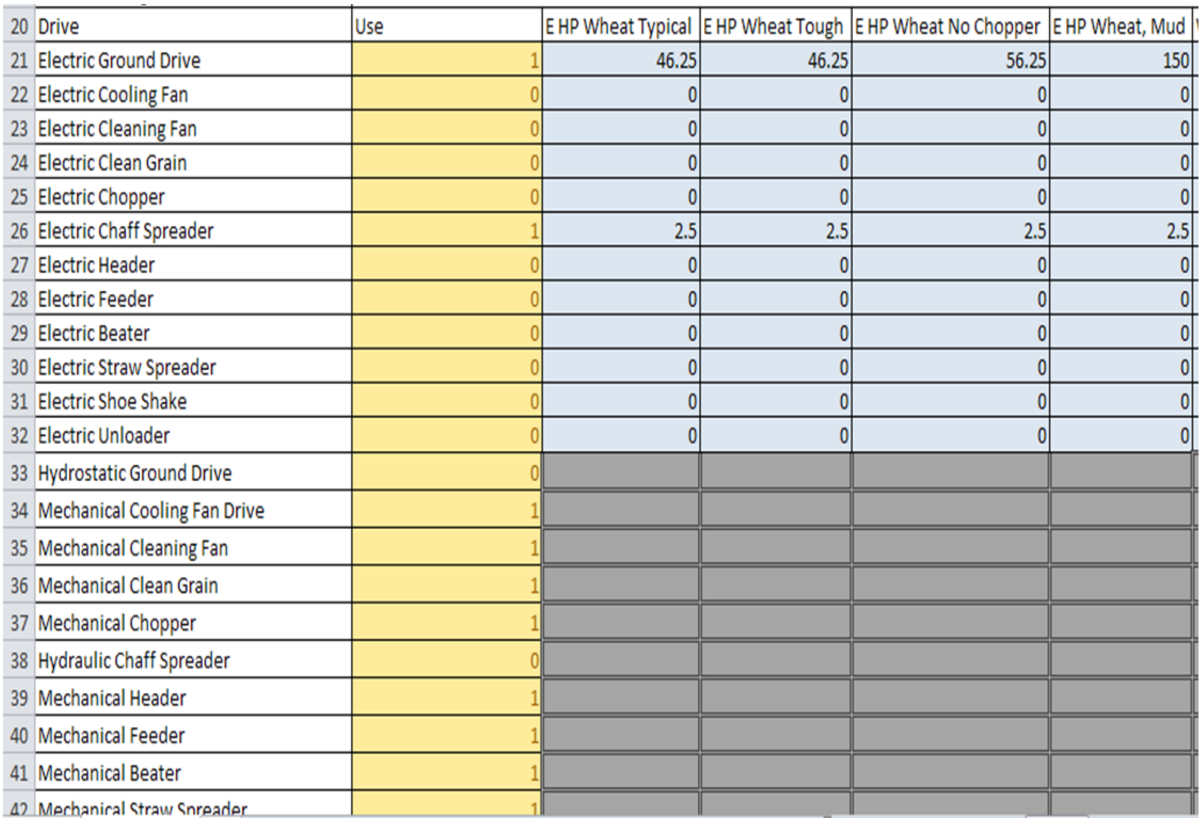


19	Scenario Weight		0.8	0.7	0.6
20	Drive	Efficiency (with cooling requirement)	HP Wheat Typical	HP Wheat Tough	HP Wheat No Chopper
21	Electric Ground Drive	0.83	44.6	44.6	54.2
22	Electric Cooling Fan	0.83	48.2	48.2	48.2
23	Electric Cleaning Fan	0.83	36.1	36.1	36.1
24	Electric Clean Grain	0.83	6.0	6.0	6.0
25	Electric Chopper	0.83	108.4	132.5	0.0
26	Electric Chaff Spreader	0.83	2.4	2.4	2.4
27	Electric Header	0.83	24.1	30.1	30.1
28	Electric Feeder	0.83	6.0	8.4	7.2
29	Electric Beater	0.83	8.4	12.0	9.6
30	Electric Straw Spreader	0.83	0.0	0.0	2.4
31	Electric Shoe Shake	0.83	12.0	12.0	12.0
32	Electric Unloader	0.83	0.0	0.0	0.0
33	Hydrostatic Ground Drive	0.55	67.3	67.3	81.8
34	Mechanical Cooling Fan Drive	0.95	42.1	42.1	42.1
35	Mechanical Cleaning Fan	0.9	33.3	33.3	33.3
36	Mechanical Clean Grain	0.9	5.6	5.6	5.6
37	Mechanical Chopper	0.9	100.0	122.2	0.0
38	Hydraulic Chaff Spreader	0.6	3.3	3.3	3.3
39	Mechanical Header	0.9	22.2	27.8	27.8

Figure 4.2 shows an example of the calculated power budget values for three use-case scenarios. The raw power required for each drive under each use-case (seen in Figure

4.1) was divided by the efficiency of the given drive to result in the total power required for each drive in each scenario. Also, note that the scenario weights were assigned in this portion of the model. The scenario weights relate to how often a typical AGCO combine customer would be expected to use the machine in each condition.

Figure 4.3: Example Power Budget Calculated Values



20	Drive	Use	E HP Wheat Typical	E HP Wheat Tough	E HP Wheat No Chopper	E HP Wheat, Mud
21	Electric Ground Drive	1	46.25	46.25	56.25	150
22	Electric Cooling Fan	0	0	0	0	0
23	Electric Cleaning Fan	0	0	0	0	0
24	Electric Clean Grain	0	0	0	0	0
25	Electric Chopper	0	0	0	0	0
26	Electric Chaff Spreader	1	2.5	2.5	2.5	2.5
27	Electric Header	0	0	0	0	0
28	Electric Feeder	0	0	0	0	0
29	Electric Beater	0	0	0	0	0
30	Electric Straw Spreader	0	0	0	0	0
31	Electric Shoe Shake	0	0	0	0	0
32	Electric Unloader	0	0	0	0	0
33	Hydrostatic Ground Drive	0				
34	Mechanical Cooling Fan Drive	1				
35	Mechanical Cleaning Fan	1				
36	Mechanical Clean Grain	1				
37	Mechanical Chopper	1				
38	Hydraulic Chaff Spreader	0				
39	Mechanical Header	1				
40	Mechanical Feeder	1				
41	Mechanical Beater	1				
42	Mechanical Straw Spreader	1				

Figure 4.3 shows an example of how the electric power budget was established for each machine configuration explored. The total power values for each drive were multiplied by a binary use value (0 meaning not used, 1 meaning used) to result in the total electric power consumed by that drive for a given machine configuration, in a given use-case. The values in the four columns in light blue in Figure 4.3 show the calculated electric

power requirement for each drive in four example use-cases. These values were then summed and compared to the total electric power generation capacity available to insure the configuration selected did not exceed the limits of the selected generator.

4.2.3 Model Inputs: Component Costs

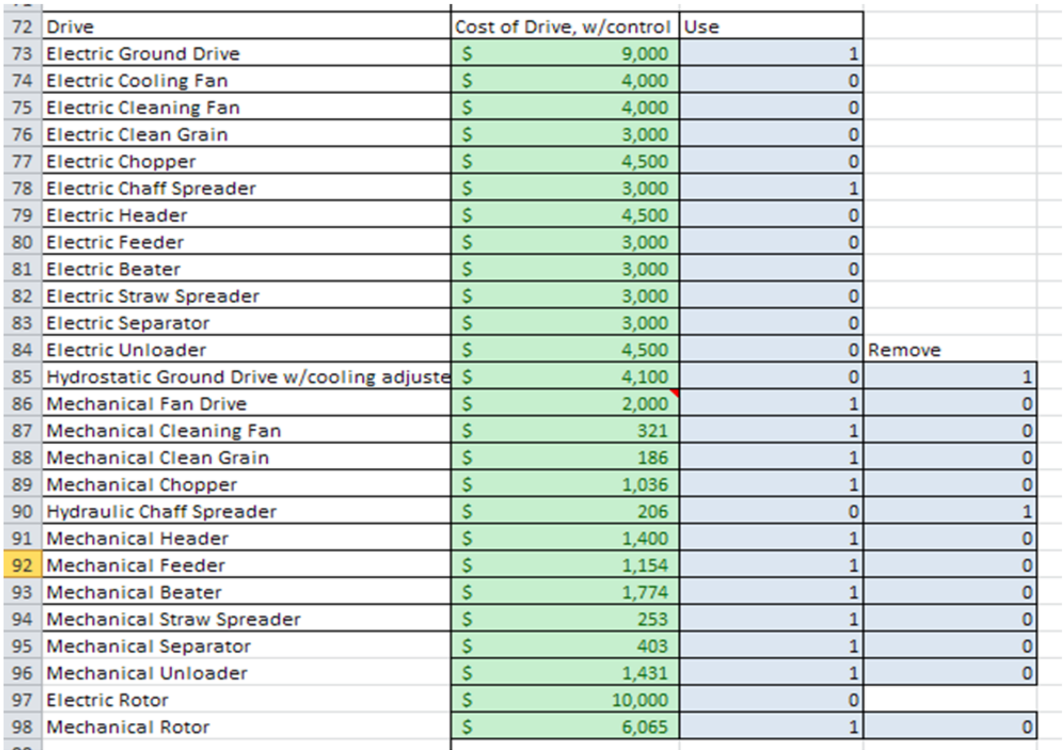
It was hypothesized that a combine harvester built with electric drives would cost more to produce, and therefore to buy, than today's machine. In order to assess the cost impact of different configurations of the existing and electric drives, a decision table was constructed with the costs of the existing drives as well as the costs of the proposed electric drives (see Figure 4.4). The costs for the existing drives were taken from AGCO's combine product cost matrix, and the costs for the proposed electric drives and controls were provided to AGCO by FEV. FEV is an engineering services provider with internationally recognized expertise in alternative transportation energy systems, and has been a major contributor to the electric drive technology utilized in the automotive and other industries today.

Another cost calculated to assess the cost difference between the existing drive configuration and proposed electric drive configurations was the cost of the electrical cabling required to move the electricity from the control unit to the motor for a given subsystem drive (see figure 4.5). The estimated cost of the cabling was figured by calculating the required size (diameter) of the cable for each drive along with the length of each cable respectively.

Once the size and length of the cable was known, the total copper weight for the cable was calculated. The total cost of the cable was assumed to be the cost of the copper contained in the cable multiplied by 1.5. Thus,

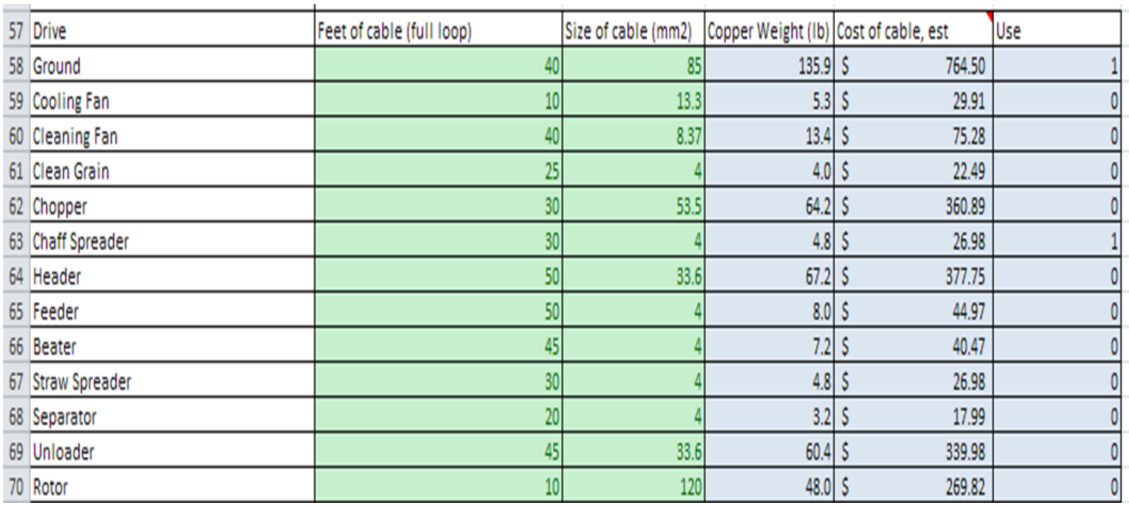
Cable cost = (Cable Length x Cable area x Density of copper x Price of copper) x 1.5

Figure 4.4: Machine Component Cost in Model



72	Drive	Cost of Drive, w/control	Use	
73	Electric Ground Drive	$ 9,000	1	
74	Electric Cooling Fan	$ 4,000	0	
75	Electric Cleaning Fan	$ 4,000	0	
76	Electric Clean Grain	$ 3,000	0	
77	Electric Chopper	$ 4,500	0	
78	Electric Chaff Spreader	$ 3,000	1	
79	Electric Header	$ 4,500	0	
80	Electric Feeder	$ 3,000	0	
81	Electric Beater	$ 3,000	0	
82	Electric Straw Spreader	$ 3,000	0	
83	Electric Separator	$ 3,000	0	
84	Electric Unloader	$ 4,500	0	Remove
85	Hydrostatic Ground Drive w/cooling adjuste	$ 4,100	0	1
86	Mechanical Fan Drive	$ 2,000	1	0
87	Mechanical Cleaning Fan	$ 321	1	0
88	Mechanical Clean Grain	$ 186	1	0
89	Mechanical Chopper	$ 1,036	1	0
90	Hydraulic Chaff Spreader	$ 206	0	1
91	Mechanical Header	$ 1,400	1	0
92	Mechanical Feeder	$ 1,154	1	0
93	Mechanical Beater	$ 1,774	1	0
94	Mechanical Straw Spreader	$ 253	1	0
95	Mechanical Separator	$ 403	1	0
96	Mechanical Unloader	$ 1,431	1	0
97	Electric Rotor	$ 10,000	0	
98	Mechanical Rotor	$ 6,065	1	0

Figure 4.5: Example Cable Cost in Model



57	Drive	Feet of cable (full loop)	Size of cable (mm2)	Copper Weight (lb)	Cost of cable, est	Use
58	Ground	40	85	135.9	$ 764.50	1
59	Cooling Fan	10	13.3	5.3	$ 29.91	0
60	Cleaning Fan	40	8.37	13.4	$ 75.28	0
61	Clean Grain	25	4	4.0	$ 22.49	0
62	Chopper	30	53.5	64.2	$ 360.89	0
63	Chaff Spreader	30	4	4.8	$ 26.98	1
64	Header	50	33.6	67.2	$ 377.75	0
65	Feeder	50	4	8.0	$ 44.97	0
66	Beater	45	4	7.2	$ 40.47	0
67	Straw Spreader	30	4	4.8	$ 26.98	0
68	Separator	20	4	3.2	$ 17.99	0
69	Unloader	45	33.6	60.4	$ 339.98	0
70	Rotor	10	120	48.0	$ 269.82	0

4.2.4 Model Inputs: Drive Efficiencies

To enable the assessment of the impact a given configuration would have on the fuel operating expense for the customer, the drive efficiencies for both the current and the proposed electric drives were introduced to the model. The efficiency levels for the existing components were provided by an industry expert in combine design (Robert Matousek, AGCO Research and Development Manager), and the efficiency levels for the proposed electric components were provided by FEV (see figure 4.2). For most of the mechanical drives in place, an efficiency of 90 percent was assigned. For the existing hydraulic drives, an efficiency of approximately 55 percent was assigned. For the proposed electric drives, an efficiency of 83 percent was assigned. These efficiency levels are general averages for each drive type, but are representative of what can be expected from the technologies commonly available today.

4.2.5 Model Calculations: Power Differential and Fuel Savings

When combined with the power use information from the weighted use-case scenarios, the efficiency level for each drive type was utilized to calculate the power consumption difference (in horsepower) of a given electric drive configuration relative to the mechanical and hydraulic configuration currently in use. It was assumed that any power savings would be translated directly in to fuel savings rather than in to increased harvest throughput. It was also assumed that, for today's drive configuration, the combine is always operated at the rated power of the engine. It was also assumed that there would be no additional fuel savings, or savings on emissions equipment, from operating the diesel engine at a more stable speed, powering a large electric generator. To equate any power savings from a given configuration to fuel savings, the amount of power saved was combined with the brake-specific fuel consumption (BSFC) for the engine (a figure generally given in pounds of fuel consumed per horsepower-hour). The BSFC of the diesel engine for this application was provided by AGCO Sisu Power, the engine manufacturing division of AGCO. The BSFC used for this analysis was 0.3 pounds per horsepower-hour. Utilizing the density of typical diesel fuel used in the United States (7.09 pounds per gallon), the BSFC was translated from pounds of fuel per horsepower-hour to gallons of fuel per horsepower-hour. Combined with the figure of horsepower saved due to efficiency gains and the price of diesel fuel, this allows the estimation of dollars saved per hour of operation.

$$\$/\text{hr} = \text{Power Difference} \times \text{BSFC} \times (1/\text{Fuel Density}) \times \$/\text{gal}$$

4.2.6 Model Calculations: Cost Differential

To calculate the cost differential for a given configuration of electrical drives relative to the cost of today's configuration, the cost of the existing drives replaced was subtracted from the cost of the electric drives added, plus the cost of the generator selected, plus the cost of the electrical cabling added. In other words, the cost of all of the components added minus the cost of all the components replaced. This total represents the cost impact to AGCO for a given configuration. It was assumed that the production labor expense would be equal for the current configuration and any proposed configuration. Seeing that auxiliary hydraulics would still be required on the machine for certain functions, it was also assumed that hydraulic reservoir and cooler expense would remain constant. Although smaller reservoir and cooling components could likely be utilized if major hydraulic drives were removed from the machine, there would also be appreciable cooling requirements for major electric drive components, so it was assumed to be equivalent to the configuration currently in use.

From AGCO's cost impact, the cost impact to the customer was figured at a 50 percent margin to retail.

4.2.7 Model Calculations: Customer Breakeven

To calculate the number of machine operation hours required for customer breakeven on the investment in a machine having electrical drives, the total cost impact to the customer was divided by the diesel fuel cost savings per hour. Sensitivity analysis was also performed to determine the breakeven point for varying fuel prices. It was assumed that there would be equal salvage values for combines with and without electric drives.

4.2.8 Model Constraints

Several constraints were utilized in the optimization model for this assessment. The first constraint states that each subsystem drive must either remain the current drive type or be converted to electric, but cannot be both. This insures that each subsystem drive requirement is satisfied, but not redundantly fulfilled. The next constraint states that the amount of electric power utilized to operate converted drives under any use-case scenario must not exceed the generation capacity available. This insures that if any drives were converted, the performance would be on par with today's offering. The remaining constraints relate to model functionality, and set bounds that the decision variables are binary and non-negative.

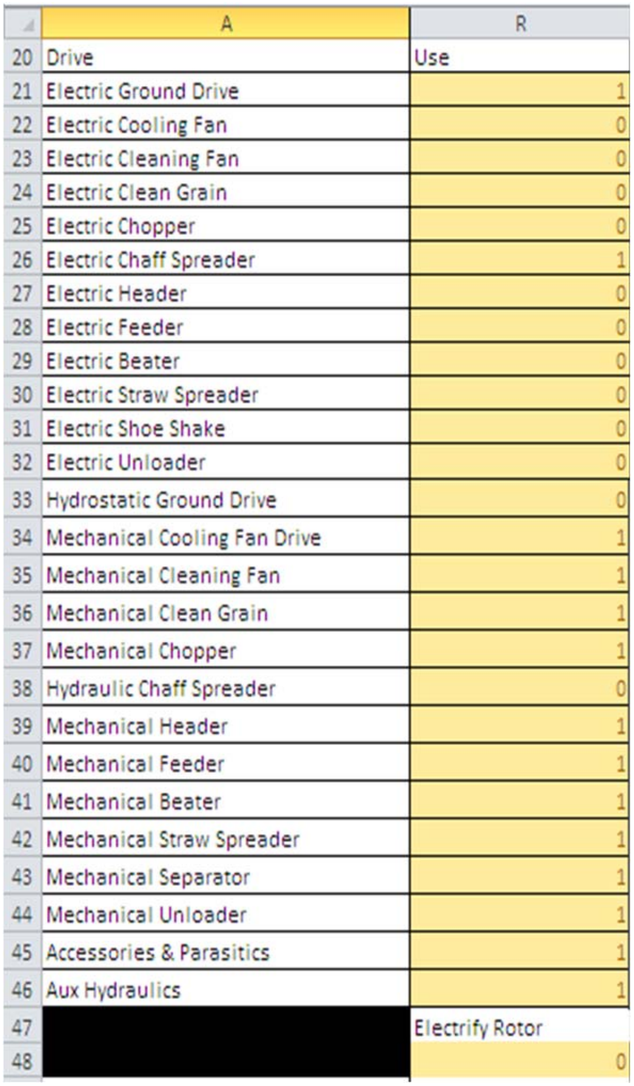
4.2.9 Model Objective

The objective of the model for this assessment was to select the optimum configuration of electric drives to minimize the number of hours of operation required to reach the breakeven point for the customer. This objective was set to find the best case scenario for the customer, and to allow for the assessment of whether this project could be feasible at this time. If the best case configuration for the customer is not acceptable at this time, it can also be concluded that none of the configurations would be feasible for the customer at this time.

4.2.10 Decision Variables

The decision variables in the model utilized for this assessment were a set of binary variables indicating whether a drive was to be utilized (see figure 4.6). Each subsystem drive had a row for both the current drive and the proposed electric drive, with a "1" indicating that the drive was to be used and a "0" indicating that the drive was not to be used.

Figure 4.6: Optimization Model Decision Variables



	A	R
20	Drive	Use
21	Electric Ground Drive	1
22	Electric Cooling Fan	0
23	Electric Cleaning Fan	0
24	Electric Clean Grain	0
25	Electric Chopper	0
26	Electric Chaff Spreader	1
27	Electric Header	0
28	Electric Feeder	0
29	Electric Beater	0
30	Electric Straw Spreader	0
31	Electric Shoe Shake	0
32	Electric Unloader	0
33	Hydrostatic Ground Drive	0
34	Mechanical Cooling Fan Drive	1
35	Mechanical Cleaning Fan	1
36	Mechanical Clean Grain	1
37	Mechanical Chopper	1
38	Hydraulic Chaff Spreader	0
39	Mechanical Header	1
40	Mechanical Feeder	1
41	Mechanical Beater	1
42	Mechanical Straw Spreader	1
43	Mechanical Separator	1
44	Mechanical Unloader	1
45	Accessories & Parasitics	1
46	Aux Hydraulics	1
47	[redacted]	Electrify Rotor
48	[redacted]	0

CHAPTER V: FINDINGS

5.1 Technical Feasibility Assessment

The literature review conducted to assess the technical feasibility of converting the existing drives on AGCO's combine harvester to electric suggested that this conversion would be technically feasible. The prior work conducted by the University of Hohenheim, as well as the successful launch and use of Caterpillar's D7E diesel-electric hybrid bulldozer, lead to the conclusion that the use of electric drives is practical in the type of working environment combine harvesters are exposed to, and that components are available to successfully power and control these drives in a form-factor suitable for use on large, mobile equipment. Seeing the success of Caterpillar's D7E bulldozer, it can reasonably be concluded that electric power components currently available commercially can withstand the harsh environment and continuous duty cycle combine harvesters are expected to operate in. Further, it can be concluded that electric power components are commercially available that will power equipment of this scale safely and without significantly changing the basic construction of the machine. FEV was able to provide general data about commercially-available families of electric components that would be suitable for use in this application. This data confirmed that the robustness of the available electric components would be suitable for use in combine harvesters, torque generation and control would be excellent, and that maintenance requirements in this application would be minimal. FEV also noted that the weight of the components would be greater than that of the existing components being replaced, but not so much as to make them impractical. For use on a machine as large as a combine harvester, the additional weight from electric drives would have a negligible impact on soil compaction.

5.2 Economic Feasibility Assessment

The economic feasibility assessment conducted suggests that converting any of the drives on AGCO's combine harvester to electric is not feasible at this time. The optimization model constructed for this assessment concluded that the most feasible configuration would be to convert the existing hydraulic ground drive and hydraulic chaff spreader drive to electric. This configuration would be a $15,985 production cost adder to AGCO over the current combine, and a $23,978 retail cost adder for the customer assuming a 50% margin to retail. Under the weighted use-case scenarios utilized for this assessment, the estimated average efficiency gain from this configuration would be 29.3 horsepower, which translates to an average fuel savings of 1.24 gallons per hour, and a customer payback of 5,518 hours of operation (well over 10 years of use for most customers) at an off-highway diesel fuel price of $3.50 per gallon. With an expected machine life of 3,000 hours of use, this means that, with current electric component and diesel fuel prices, a customer would not experience any economic benefit from the electric drives over the usable life of the machine.

5.2.1 Sensitivity Analysis

Seeing that adding electric drives to AGCO's combine harvester is not economically feasible at this time, a sensitivity analysis was conducted to determine under which circumstances it could become viable. Assuming a usable design life of 3,000 harvesting hours for the machine, it would be desirable for the added expense of installing electric drives to be offset by efficiency gains in no more than half that time—or 1,500 harvesting hours. This would allow a customer to reap an economic benefit from fuel savings over half of the machine's usable life, and offer a return equal to the initial investment in the electric drives. To reach this target, assuming the cost of the electric components installed was to stay fixed, diesel would need to be at a price of around $13 per gallon (see Figure 5.1). If it is assumed that the price of diesel is fixed at $3.50 per gallon, the retail cost of adding the electric components would need to drop to only $6,500 over the cost of today's machine (see Figure 5.2). Expressed in other terms, this would be a 73 percent reduction in electric component costs compared to the estimated costs used from the current market. To cite a few more possible scenarios, should the price of diesel jump to $5 per gallon, the cost added by the electric components would need to be less than about $9,000, and at $7 per gallon, the added cost of the components would need to be less than about $13,000. If technological advances were made to electric drive components to bring the efficiency up from 83 percent to 90 percent, with all else held constant, the payback period would drop from 5,518 to 4,780 harvesting hours. While this would be an improvement, even at this level of efficiency the cost of adding the electric drives is high enough to make the conversion economically impractical.

Figure 5.1: Time to Customer Breakeven vs. Diesel Fuel Price

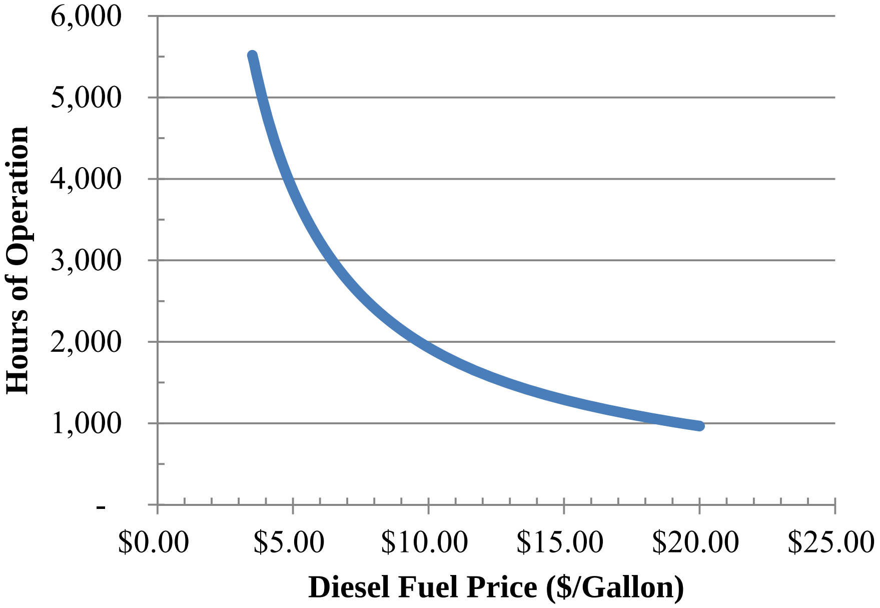
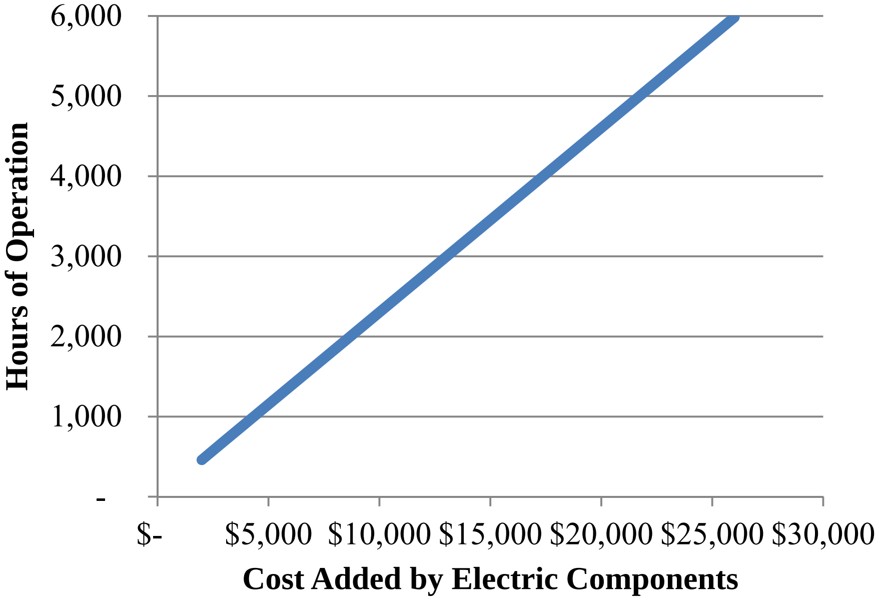


Figure 5.2: Time to Customer Breakeven vs. Retail Cost Added by Electric Components--$3.50 per gallon Diesel Fuel Price



CHAPTER VI: CONCLUSION

In conclusion, while this study did show that it is technically feasible for AGCO to construct a combine harvester with electric drives, it is not yet economically feasible to do so. The literature reviewed indicates that all of the required technologies exist to produce a functional and reliable combine, and a university has actually done so. However, even after uncovering the most cost-effective solution, the economic analysis shows that the added expense of the electric drives is simply too great, and the efficiency gains too small, to allow fuel efficiency improvements to provide a monetary benefit for the customer over the useful life of the machine. Ultimately, although the prospect of installing electric drives on combine harvesters is exciting, the technology is simply not yet affordable enough to provide value to AGCO's customers.

Although electric drive technology has started to take a foot-hold in the construction equipment business, the usable machine lifetime and use of hydraulic power is much more prevalent than in combine harvesters; making the outcome of the economic analysis look much different. Due to the extreme cost that it would add, it would be impractical to increase the design life of combine harvesters to make the use of electric drives attractive. Perhaps once off-highway electric drive technology matures in the construction industry, component costs and efficiencies will improve to the point where they will become economically viable for use in combine harvesters. However, this does point to the possibility of electric drives being feasible on other types of agricultural machinery that are heavily reliant on hydraulic drives—such as self-propelled windrowers and sprayers.

This thesis only begins to delve in to the possibilities for diesel-electric hybrid drives for combine harvesters. In the future, further consideration should be given to possible performance improvements which could be obtained by converting to electric drives, and the impact that the additional monitoring and control functionality offered by electric drives could have on marketability and overall harvest efficiency.

In addition, further consideration could be given to combining different drives, powering a section of the machine with one, larger electric motor rather than an individual motor for each drive. While this would limit the capability for individual drive monitoring and control, if electric drive component costs are sufficiently low, the cost of getting mechanical power to some areas of the machine could potentially be reduced.

It should also be determined how designing the proposed electric drives to operate only at one speed would have on the feasibility of this conversion. Operating certain drives straight from the electrical power generation unit, rather than moving through inverters and controls, would reduce the complexity, cost, and weight of the system; while driving up the efficiency. All of these things would be positive for the economic feasibility of converting to electric drives. However, going about the conversion in this manner would not provide any additional functionality or features for the end-user over today's offering, therefore limiting the market appeal if the machine cost, or operating expense, could not be reduced significantly.

It also merits mentioning that converting to electric drives, especially if no marketable functionality was added to enable passing cost on, would increase the commodity price risk in manufacturing these machines. Due to the addition of a large amount of copper, and rare-earth materials in some cases, in the generation unit, controls, cables, and motors, additional component price risk linked to these commodities would be taken on if electric drives are added to the machine. Instability in copper price has been experienced in the recent past, and proper analysis and risk management procedures should be explored before deciding to pursue manufacturing any product with major electric drives.

The most significant items for future consideration of adding electric drives to AGCO's combine harvester will be improvements in the cost and efficiency of electric drive components for mobile equipment, as well as the cost of diesel fuel. AGCO should stay in-tune with the most recent advances in electric drive technology, and be prepared to move forward should the economic conditions shift toward being conducive to marketing a combine harvester with major electric drives.

WORKS CITED

AGCO Corporation. *Fendt Combines.* 2012. http://www.fendt.com/int/5514.asp (accessed December 8, 2012).

Amanor-Boadu, Dr. Vincent. *Assessing the Feasibility of Business Propositions.* Manhattan, Kansas: Kansas State University, 2003.

B. Bernhard, V. R. Schlotter. *ELECTRIC DRIVES FOR COMBINE HARVESTERS.* Proceedings of the International Conference on Crop Harvesting, Louisville, Kentucky: ASABE, 2003.

Caterpillar. "D7E." *Caterpillar.* 2013. http://www.cat.com/D7E (accessed January 24, 2013).

Cornways. *Cornways--History*. n.d. http://www.cornways.com/hi_combine.html (accessed December 8, 2012).

Hampton, Tudor Van. "Cat Reveals Pricing of World's First Hybrid Dozer." *Engineering News-Rocord.* June 24, 2009. http://enr.construction.com/products/equipment/2009/0624-CATRevealsHybridDozer.asp (accessed January 24, 2013).

Jürgen Karner, Heinrich Prankl, Florian Kogler. *Electric Drives in Agricultural Machinery.* Future Farm Technology Report, Vienna, Austria: Austrian Research Promotion Agency, 2011.

Korrane, Kenneth J. "Hybrid Drives for Construction Equipment." *Machine Design.* July 7, 2009. http://machinedesign.com/article/hybrid-drives-for-construction-equipment-0707 (accessed January 24, 2013).

Rostselmash. "Rostselmash Product Information." *Rostselmash.* n.d. http://www.rostselmash.com/download/rsm_eng_SMALL.pdf (accessed November 11, 2012).