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Economic Viability of Ultrasonic Sensor Actuated Nozzle Height Control in Center Pivot Irrigation Systems

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Abstract: The coverage of center pivot irrigation systems used around the world has increased. One potential factor driving their adoption is improved water application efficiency relative to some other sprinkler or surface irrigation approaches. Center pivot irrigation systems may be further improved by dynamic elevation spray application (DESA). DESA systems adjust the nozzle height in response to plant growth and canopy heterogeneities. The DESA approach is relatively new and there is uncertainty in its economic viability and worthiness of further investigation. Thus, an economic scenario analysis was performed to explore the potential economic benefits of DESA based on permutations of irrigation pivot efficiency without DESA, water-saving potential of DESA, and water cost. The weighted costs and benefits of the height-adjusted approach for a set of water cost savings scenarios showed the net return price with the water cost savings per season. We show that DESA could have economic viability at current component costs and is worthy of further investigation and refinement.

Keywords: DESA; Arduino; economic feasibility; HC-SR04 ultrasonic sensor

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1. Introduction

Center pivot irrigation systems, invented in the mid-20th century, are now used around the world in field cropping systems. There has been an evolution of the center pivot designs driven by a need to increase irrigation efficiency and reduce costs by minimizing water loss, design, and installation costs [1]. For example, the mid-elevation spray application (MESA), the low-elevation spray application (LESA), the low-energy precision application (LEPA), variable irrigation rate (VIR), and mobile drip systems have been developed to increase application efficiency and reduce energy [1]. Ortiz et al. used two types of sprinkler irrigation systems (rotating spray plate sprinklers and fixed spray plate sprinklers) to study evaporation and drift losses [2]. They installed systems 1 m and 2.5 m above the ground and found significant evaporation and drift losses with fixed spray plate sprinklers at 2.5 m compared to the rotating spray plate sprinklers at 1 m. Another study found lower evaporation and drift losses when the sprinklers are near the ground [3].

The initial cost of specialized systems can be higher than that of traditional center pivot systems [1,4–7]. Hall and Lacewell assessed the relative economic costs and benefits of LEPA, surface drip irrigation (SDI), and furrow irrigation (FI) with an annual budgeting method and showed that LEPA was the most economical method [8]. Other studies have concluded that SDI is the most economical approach on smaller farms; the finding has been attributed to lower investments costs per hectare, lower pumping costs, and increased yields [9,10]. Contemporary efficiency gains were achieved by integrating center pivot systems with next-generation emitters, and by altering the fixed height of those emitters [1,11]. Such adaptations and design improvements demand substantial economic and resource gain [4]. Dhuyvetter, Lamm, and Rogers demonstrated the economic benefits of center pivots over other systems [12,13]. Technology adoption and innovation can be a pathway to support sustainable water management and reduce food shortages [14] and save energy [15]. Center pivot innovation can be a part of a collective effort to close the sustainability gap, which will also include multiple approaches such micro-irrigation adoption [16,17], minimal climate change impacts, reduced food waste, and additional transformative innovations such as smart greenhouses and agrivoltaic systems [18].

In this paper, we evaluate a next step in the evolution of center pivots: dynamically adjusting the emitter position relative to the plant canopy to minimize losses in a real-time-dynamic elevation spray application (DESA) [19,20]. We evaluate the economic feasibility of DESA through a cost analysis that considers three water savings assumptions to determine. Economic constraints informed the design decisions and dictate low-cost components to be used. The technical feasibility of DESA is then assessed by exploring the viability of a low-cost sensor to provide the key data input into the feedback-control cycle: nozzle height relative to the crop canopy. We hypothesized that a DESA center pivot with advanced sensing and nozzle height control would improve water distribution and management and has the potential to increase profitability.

The objective of the present study was to evaluate the economic and technical feasibility of DESA. This was achieved by performing an economic analysis for the feasibility of the deployment of such sensors for various cropping systems and comparing the net returns/gains with those of a conventional system.

2. Material and Method

2.1. Cost Estimates

The base case center pivot (CP) is a 305 m device irrigating 33 ha (81 acres) operating at 41.4 kPa. Electrical inputs are evaluated using the state commercial electricity supply (USD 0.1/kW-hr). The total time required to apply 1.27 cm over 33 ha was calculated as 33 h. The financial analysis considered (a) power requirements, (b) set up (CP system) and DESA assembly (present study), (c) sprinkler system, (d) pumps, and (e) bore well. The costs are provided in Table 1.

Table 1. Infrastructure and Initial Investment Cost.

Item Unit Quantity Cost/Unit Total per ha	Quantity	Cost/Unit (USD)	Total Cost	USD per ha
Power service	1	2000	2000	60.61
8 inch PVC pipe and fittings (feet)	1000	7.20	7200	218.18
Sprinkler System (5 towers = 50 m * 5 = 250 m)	1	52,543	52,543	1592.21
Pump motor, 40 HP	1	15,000	15,000	454.55
Bore well	1	27,500	27,500	833.33
Total investment cost			**USD 104,243**	**USD 3158.88**

The total calculated annual cost included the total fixed cost (assets and infrastructure) and the total operational and maintenance costs including repair and replacement, water costs, and energy costs. Annual asset depreciation was calculated using straight-line depreciation. The net present value (NPV) sensor cost and its integration into the conventional setup were calculated and recorded annually at a discounted rate of 12.5%. Interest rates for the various assets were based on specified figures and were calculated as the mean of the initial cost plus the salvage value multiplied by the rate of interest (i.e., 8.5% on assets and 1.4% on taxes and insurance). In addition, the cost of the assembly was computed to determine the final cost of the base system with and without DESA. The initial center pivot system cost to cover 33 ha would be USD 104,000. The next step was to include the water savings to determine the final cost of including DESA into the base system.

2.2. DESA Components, and Low-Cost Sensor Test

DESA-enabled pivots would require that each nozzle be associated with a sensor, a microprocessor, and a motorized means to adjust the position of the nozzle head. DESA connects to a microcontroller, like Arduino [21]. Ultrasonic distance sensors (model HC-SR04) have an established work history with Arduino in agricultural and environmental applications. Al-agele et al. [20] presented the fully constructed DESA prototype. The Arduino UNO R3 Mega 2560 (<USD 15) was selected for sensor design and control for the present study. The sensor is positioned 0.2 m above the nozzle to protect the sensor from the water, and all electronic parts are secured inside high-density polymer enclosures. This basic design contains a flange, 0.019 m (45 degree) elbow, 0.077 m (90 degree) elbow, PVC expansion fitting, with additional parts made by a laser cutter and a 3-D printer. The total cost of the components used to construct the prototype was USD 72, with about half of that cost allocated to the DC motor. A DESA design and full breakdown of the component costs is presented in Figures 1 and 2.

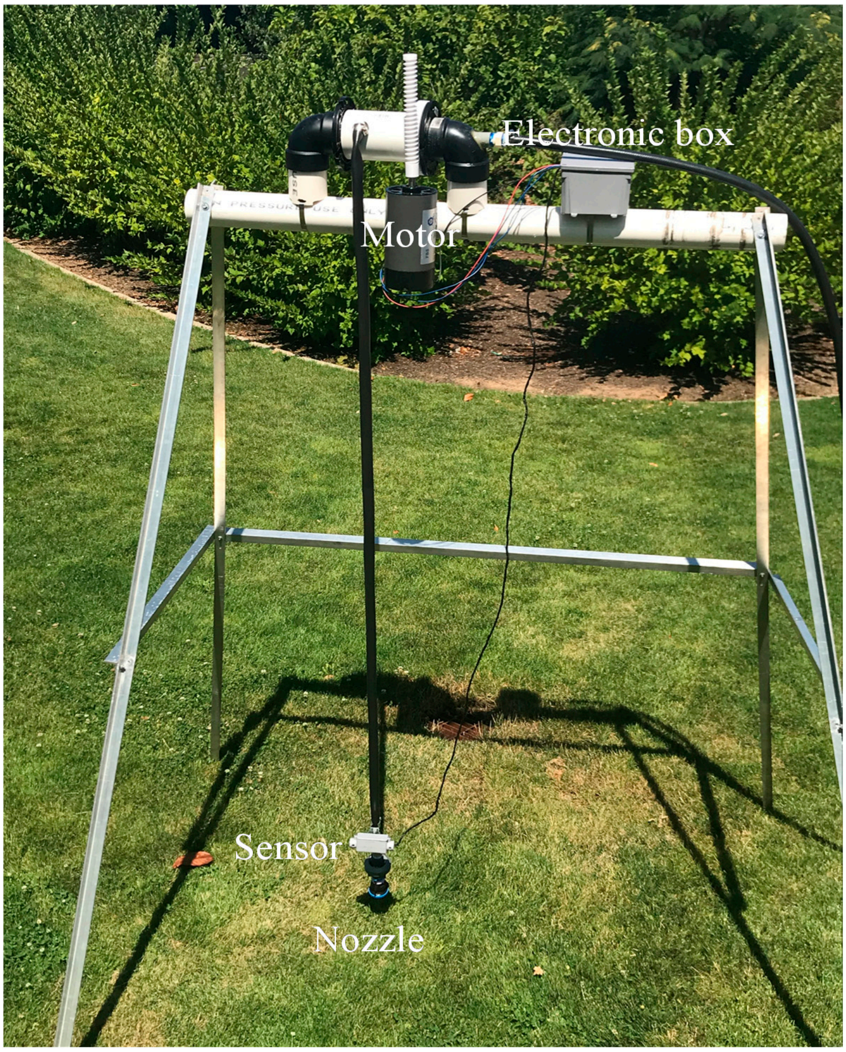

Figure 1. Snapshot for DESA designed and tested with all components to rotate hosepipe back and forth connected with an electronic board assembly with circuits.

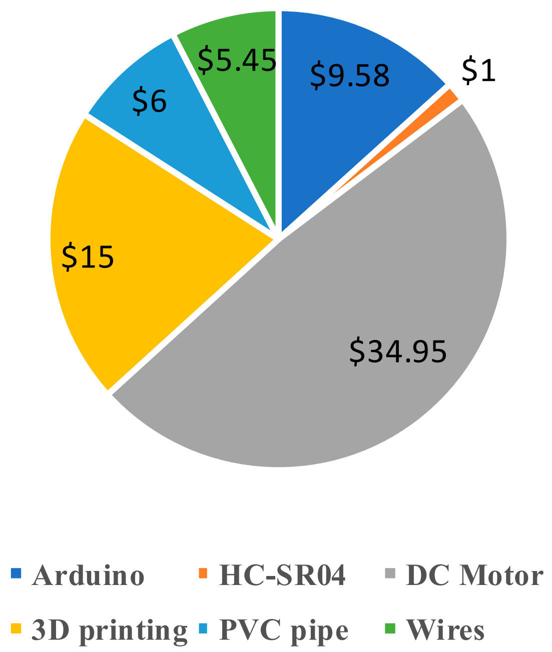

Figure 2. Prototype cost breakdown by component.

2.3. Calculation of Water Losses in the Center Pivot Irrigation System

A typical 33 ha center pivot irrigation system may apply 160 cubic meters of water per irrigation event [22] and up to 132,000 cubic meters per season. These amounts do vary by crop and local on-the-ground conditions. Water pumping costs also vary depending on water source location with particular differences between rivers and wells [23]. A center pivot applies this water with an approximate water application efficiency of 85% [24] with the 15% water loss caused by wind drift and evaporation. Water loss by wind drift comprises the majority of losses and accounts for 50–70% [25] of the lost water fraction, see Table 2. Thus, our later analysis explores the range of these values, e.g., 50%, 60%, and 70% wind drift loss percentages are explored.

Table 2. Irrigation water lost by wind draft during an irrigation event from the center pivot irrigation method.

Areas (ha)	Water Loses by Wind Draft (m^3)		
	0.5	0.6	0.7
1	12	14.4	16.8
33	396	475.2	554.4
per season for 33 ha	9900	11,880	13,860

The total irrigation water loss per area was calculated as the water loses percentage from wind draft times application efficiency losses in the center pivot irrigation times total water applied per area [24,25].

The wind drift losses of center pivot irrigation may be reduced by DESA, which would result in higher application efficiency. This is achieved by adjusting the relative position of the droplet nozzle automatically and reducing the distance between the plant canopy and the nozzle. Potential water savings can be projected by assuming a reduction in wind drift losses for each of the considered scenarios: 50%, 60%, and 70%. This exploration of the potential scenarios is presented in Table 3. DESA cannot eliminate the losses due to wind drift, only reduce them. To compute the potential water savings, we explored the potential of DESA to reduce wind drift by 15%, 25%, 35%, 45%, 55%, and 65% to save water from wind drafts during the irrigation event (Equation (1)). Values are presented in Table 3.

Total water saving per area = water-saving percentage * total water loss by wind draft per area (1)

Table 3. Water-saving during irrigation event by using a DESA design with center pivot irrigation.

Areas (ha)	Fraction of Wind Drift Reduced by DESA (m^3)					
	0.15	0.25	0.35	0.45	0.55	0.65
1	1.8	3.6	5.88	5.4	7.92	10.92
33	59.4	118.8	194.04	178.2	261.36	360.36
per season per 33 ha	1485	2970	4851	4455	6534	9009

There is a wide range in the price paid for irrigation water in the United States which ranges from USD 0.005 per m^3 to USD 0.01 per m^3 with some States having elevated prices from irrigation water becoming more expensive from USD 0.02 to more than USD 0.10 per m^3 [26]. D'Odorico et al. determined that the global irrigation water prices for five major crops Wheat, Maize, Rice, Soybean, and Potatoes are USD 0.05/m^3, USD 0.16/m^3, USD 0.10/m^3, and USD 0.67/m^3, respectively [27]. Water values ranging from USD 0.005 to $0.10 per m^3 are used in the analysis below to determine the value of the lost water in the calculations below (Tables 4 and 5).

Table 4. Irrigation water price lost by wind drift during an irrigation event in center pivot irrigation.

Area (ha)	Irrigation Water Price Lost by Wind Draft		
		USD 0.01	
	0.5	0.6	0.7
1	0.06	0.07	0.08
33	1.98	2.38	2.77
per season for 33 ha	49.50	59.40	69.30
		USD 0.01	
1	0.12	0.14	0.17
33	3.96	4.75	5.54
per season for 33 ha	99.00	118.80	138.60
		USD 0.02	
1	0.24	0.29	0.34
33	7.92	9.50	11.09
per season for 33 ha	198.00	237.60	277.20
		USD 0.10	
1	1.20	1.44	1.68
33	39.60	47.52	55.44
per season for 33 ha	990.00	1188.00	1386.00

Table 5. Irrigation water price saving by the DSEA design during an irrigation event.

Area (ha)	Irrigation Water Price Saving by Using a DESA Design		
		USD 0.005	
	0.15	0.25	0.35
1	0.01	0.02	0.03
33	0.30	0.59	0.97
per season for 33 ha	7.43	14.85	24.26
		USD 0.01	
1	0.02	0.04	0.06
33	0.59	1.19	1.94
per season for 33 ha	14.85	29.70	48.51

Table 5. *Cont.*

Area (ha)	Irrigation Water Price Saving by Using a DESA Design		
		USD 0.02	
1	0.04	0.07	0.12
33	1.19	2.38	3.88
per season for 33 ha	29.70	59.40	97.02
		USD 0.10	
1	0.18	0.36	0.59
33	5.94	11.88	19.40
per season for 33 ha	148.50	297.00	485.10
		USD 0.005	
	0.45	0.55	0.65
1	0.03	0.04	0.05
33	0.89	1.31	1.80
per season for 33 ha	22.275	32.67	45.045
		USD 0.01	
1	0.05	0.08	0.11
33	1.78	2.61	3.60
per season for 33 ha	44.55	65.34	90.09
		USD 0.02	
1	0.11	0.16	0.22
33	3.56	5.23	7.21
per season for 33 ha	89.1	130.68	180.18
		USD 0.1	
1	0.54	0.79	1.09
33	17.82	26.14	36.04
per season for 33 ha	445.5	653.4	900.9

3. Results and Discussion

3.1. Irrigation Water Value Lost by Wind Drift Additionally, Savings with DESA

The value of water lost to wind drift is presented in Table 4. Furthermore, the potential value of the wind drift reduction potential of DESA is presented in Table 5. The values are highly dependent on the situation and circumstances of an individual system and can span across two orders of magnitude.

3.2. Climate Change

Climate change may also play a role in wind drift loss in the future. First, climate change affects wind speed which leads to increased evapotranspiration (ETo) from the crops [28] and potential evapotranspiration (PET). This leads to rising crop water requirement (CWR) [29]. Thus, if loss fractions are similar, the water lost by wind drift would increase proportionately in absolute terms. The increased water demands may also lead to increased water costs in the future. This, coupled with the cited literature on localized higher costs of water necessitated the inclusion of scenarios (USD 0.15, USD 0.20, and USD 0.25). The result is presented in Table 6. In addition, water-saving from the DESA system in the same scenarios is presented in Table 7.

Table 6. Irrigation water price lost by wind drift during an irrigation event in center pivot irrigation affected by climate change.

Area (ha)	Irrigation Water Price Lost by Wind Drift		
		USD 0.15	
1	1.80	2.16	2.52
33	59.40	71.28	83.16
per season for 33 ha	1485.00	1782.00	2079.00
		USD 0.20	
1	2.40	2.88	3.36
33	79.20	95.04	110.88
per season for 33 ha	1980.00	2376.00	2772.00
		USD 0.25	
1	3.00	3.60	4.20
33	99.00	118.80	138.60
per season for 33 ha	2475.00	2970.00	3465.00

Table 7. Irrigation water price saving by a DSEA design during an irrigation event with climate change.

Area (ha)	Irrigation Water Price Saving by a Using DESA Design		
		USD 0.15	
	0.15	0.25	0.35
1	0.27	0.54	0.88
33	8.91	17.82	29.11
per season for 33 ha	222.75	445.50	727.65
		USD 0.20	
1	0.36	0.72	1.18
33	11.88	23.76	38.81
per season for 33 ha	297.00	594.00	970.20
		USD 0.25	
1	0.45	0.90	1.47
33	14.85	29.70	48.51
per season for 33 ha	371.25	742.50	1212.75
		USD 0.15	
	0.45	0.55	0.65
1	0.81	1.188	1.638
33	26.73	39.204	54.054
per season for 33 ha	668.25	980.1	1351.35
		USD 0.20	
1	1.08	1.584	2.184
33	35.64	52.272	72.072
per season for 33 ha	891	1306.8	1801.8
		USD 0.25	
1	1.35	1.98	2.73
33	44.55	65.34	90.09
per season for 33 ha	1113.75	1633.5	2252.25

3.3. Economic Viability of DESA

We hypothesized that the increased cost of DESA can be offset by increased efficiency in either water, fertilizer, pesticide, or herbicide use. In the most conservative case, these savings would come from water use alone. Thus, a series of water savings scenarios (50% to 70%) were explored and the irrigation water saving price of the DESA system per season as a function of hypothetical water savings was calculated. These water-saving prices are presented in Table 3. To calculate the total saving price after using the DESA system during the season, one needs to know the total price of the DESA system per area. The total price of the DESA system can be calculated by Equation (2).

$$\text{The total cost of DESA system per area} = (\text{price per nozzle}) * (\#\text{ nozzles on 33 ha center pivot}) \quad (2)$$

Total cost of DESA system per area = USD 72 * 50 = USD 3600

The total price for DESA design is USD 3600 to cover 33 ha with center pivot irrigation. A conservative assumption is that the unit price for DESA should be lower. The systems that control individual nozzles must be made inexpensively from low-cost components for DESA to be economically viable. Improvements in the productivity of the crops due to better water distribution, water use efficiency, and savings in fertilizers and pesticides/herbicides owing to low water inputs could further improve the net returns and profits. However, all potential benefits (including verified water savings potential) are, as of this publication, not yet demonstrated for DESA. Investigations on the effects of DESA are needed for a more robust economic analysis. However, such outcomes would be dependent on nature and the type of crop, the topography, the pedosphere, and the weather conditions.

The DESA profits rise with increased water cost and application efficiency (efficiency gains through reduced wind drift). The net returns per season are calculated by Equation (3) and the results shown in Tables 8 and 9 with climate change in the future with new water cost assumptions

$$\text{Total water cost savings per season} = (\text{irrigation water saving per season}) * (\#\text{seasons/year}) * (\text{4-year payback period}) \quad (3)$$

Table 8. Irrigation water saving per season at three percentage assumptions for water-saving by using a DESA design with center pivot irrigation at different water prices.

Season	The Total Irrigation Water Price Saving Per Season with a DESA Design											
		USD 0.01			USD 0.01			USD 0.02			USD 0.10	
	0.15	0.25	0.35	0.15	0.25	0.35	0.15	0.25	0.35	0.15	0.25	0.35
1	30	59	97	59	119	194	119	238	388	594	1188	1940
2	59	119	194	119	238	388	238	475	776	1188	2376	3881
3	89	178	291	178	356	582	356	713	1164	1782	3564	5821
4	119	238	388	238	475	776	475	950	1552	2376	4752	7762
		USD 0.005			USD 0.01			USD 0.02			USD 0.1	
	0.45	0.55	0.65	0.45	0.55	0.65	0.45	0.55	0.65	0.45	0.55	0.65
1	89	131	180	178	261	360	356	523	721	1782	2614	3604
2	178	261	360	356	523	721	713	1045	1441	3564	5227	7207
3	267	392	541	535	784	1081	1069	1568	2162	5346	7841	10,811
4	356	523	721	713	1045	1441	1426	2091	2883	7128	10,454	14,414

3.4. Calculation of the Installation, Maintenance, and Operation Including DESA System

Fixed costs for the installation, maintenance, and operation of the center pivot (base case) were USD 104,243 (USD 3158.88/ha). The integration of DESA into the base case increases those costs by an amount that depends on the DESA's investment capital cost. The annual fixed cost was calculated based on the initial investment costs. It is assumed that the resale value of the assets at the end of their useful life is negligible. Moreover, depreciation is calculated based on the lifespan of the assets and their utilities only. The lifespan of the DESA assembly was assumed to be 20 years, but other lifespan estimates could also be explored. The lifespans of the other assets range from 10-25 years [25]. The sum of the depreciation cost (1), the rate of interest (8.5%; 2), taxes, and insurance (1.4%; 3) (DITI) are summed (Table 10). For an example calculation, we set DESA unit costs to the current prototype cost (USD 72 each) and show a total fixed cost of USD 107,842 and a depreciation cost of USD 5812, i.e., ~5% of the Investment cost.

Table 9. Irrigation water saving per season at three percentage assumptions for water-saving by using a DESA design with center pivot irrigation at different water prices with climate change in the future.

Season	The Total Irrigation Water Price Saving Per Season with a DESA Design								
		USD 0.15			USD 0.20			$0.25	
	0.15	0.25	0.35	0.15	0.25	0.35	0.15	0.25	0.35
1	891	1782	2911	1188	2376	3881	1485	2970	4851
2	1782	3564	5821	2376	4752	7762	2970	5940	9702
3	2673	5346	8732	3564	7128	11,642	4455	8910	14,553
4	3564	7128	11,642	4752	9504	15,523	5940	11,880	19,404
		USD 0.15			USD 0.20			USD 0.25	
	0.45	0.55	0.65	0.45	0.55	0.65	0.45	0.55	0.65
1	2673	3920	5405	3564	5227	7207	4455	6534	9009
2	5346	7841	10,811	7128	10,454	14,414	8910	13,068	18,018
3	8019	11,761	16,216	10,692	15,682	21,622	13,365	19,602	27,027
4	10,692	15,682	21,622	14,256	20,909	28,829	17,820	26,136	36,036

3.5. Calculation of the Installation, Maintenance, and Operation Including DESA System

Fixed costs for the installation, maintenance, and operation of the center pivot (base case) were USD 104,243 (USD 3158.88/ha). The integration of DESA into the base case increases those costs by an amount that depends on the DESA's investment capital cost. The annual fixed cost was calculated based on the initial investment costs. It is assumed that the resale value of the assets at the end of their useful life is negligible. Moreover, depreciation is calculated based on the lifespan of the assets and their utilities only. The lifespan of the DESA assembly was assumed to be 20 years, but other lifespan estimates could also be explored. The lifespans of the other assets range from 10-25 years [25]. The sum of the depreciation cost (1), the rate of interest (8.5%; 2), taxes, and insurance (1.4%; 3) (DITI) are summed (Table 10). For an example calculation, we set DESA unit costs to the current prototype cost (USD 72 each) and show a total fixed cost of USD 107,842 and a depreciation cost of USD 5812, i.e., ~5% of the Investment cost.

Annual operating costs were also tabulated. A 2% repair and maintenance charge for DESA was assigned. The total fuel expenditure (electricity reported as KWH) is USD 29.61 per ha. There are no costs associated with repairs and maintenance of the power delivery. The sum of annual costs (fixed and operating costs) for DESA was computed to be USD 13,169 (USD 399.06/ha). This is 1.1% higher than the USD12,104 (USD 366.79/ha) cost of the conventional center pivot without DESA.

Table 10. Economic analysis of a CPD-based irrigation system featured with the sensor assembly.

I. ANNUAL FIXED COSTS								
Particulars	**Investment Cost**	**Salvage Value**	**Useful Life Years**	**Depreciation (1)**	**Interest(2) (8.5%)**	**Tax and Insurance (3) (1.4%)**	**Total (1 + 2 + 3) DITI**	**Total Per ha**
Power service	USD 2000	USD 0.00	10	USD 200.00	USD 85.00	USD 14.00	USD 299	USD 9.06
8 inch PVC pipe and fittings	USD 7200	USD 0.00	20	USD 360.00	USD 306.00	USD 50.40	USD 716	USD 21.70
DESA module *	USD **3599**	USD **0.00**	**20**	**USD 500.00**	**USD 425.00**	**USD 140.00**	**USD 1065**	USD 32.27
Sprinkler System (5 towers)	USD 52,543	USD 0.00	20	USD 2627.15	USD 2233.08	USD 367.80	USD 5228	USD 158.42
Pump motor, 40 HP	USD 15,000	USD 0.00	20	USD 750.00	USD 637.50	USD 105.00	USD 1493	USD 45.24
Well	USD 27,500	USD 0.00	20	USD 1375.00	USD 1168.75	USD 192.50	USD 2736	USD 82.91
TOTAL FIXED COST	USD **107,842**			**USD 5812.15**	**USD 4855.33**	**USD 869.70**	**USD 11,537**	**USD 350**
II. ANNUAL OPERATING COST								
Fuel		**No. of Hours/ Irrigation Event**	**Rated Horse Power**	**Fuel Use (KWH/HP/hr)**	**Fuel Cost (USD/KWH)**	**# Irrigation Events**	**Total**	**Total Per ha**
Electricity		65.5	40	0.746	USD 0.10	10	USD 977	USD 29.61
Repairs and Maintenance	**Initial Cost**	**Cost Factor**						
Power service	USD 2000	0.00%					USD 0	USD 0.00
DESA module *	**USD 3599**	**2.00%**					**USD 72**	**USD 2.18** **USD 2.47**
8 inch PVC pipe and fittings	USD 7200	0.00%					USD 0	USD 0.00
Sprinkler System (5 towers)	USD 52,543	0.50%					USD 263	USD 7.97
Pump motor, 40 HP	USD 15,000	2.00%					USD 300	USD 9.09
Well	USD 27,500	0.00%					USD 0	USD 0.00
Labor—Irrigation	**Hours**	**Cost/hour**						
Labor	2	USD 10.00					USD 20	USD 0.61
			TOTAL OPERATING COST				**USD 1632**	**USD 49.45**
	III. TOTAL ANNUAL COST						**Total**	**per ha**
			TOTAL FIXED AND OPERATING COST				**USD 13,168.98**	**USD 399.06**

* The base case excludes the sensor modules.

4. Conclusions

This work illustrates the potential of open, inexpensive, networked hardware to combine with modern precision agriculture through the DESA example. The DESA example was chosen to explore its potential and to determine if such an approach was worthy of further experimentation and refinement. We conclude that it is. DESA makes nozzle-level information and adaptive control possible with off-the-shelf components and a component an assembly costing USD 72. DESA could become economically viable, as shown in the analysis above, in scenarios of higher water cost and climates with multiple annual growing seasons.

Additional DESA benefits, not considered in the economic calculations, could further increase its value and potential. For example, the information and data gathered by the DESA system may also have value to growers as it can be used to create dynamic maps of canopy growth throughout the growing season which could be used to identify locations of reduced productivity. DESA could also adapt to the presence of multiple crop canopies in a single field if a diverse planting layout or intercropping approach were strategically advantageous. Additional economic savings associated with chemigation may also be anticipated. The combination of these potential benefits and the scenario-dependent water savings indicate that DESA is an irrigation approach worthy of future investigation.

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References

1. New, L.; Fipps, G. Center Pivot Irrigatio. In *Proceedings of Texas Farmer Collect*; Texas A&M University: College Station, TX, USA, 2000; Available online: https://hdl.handle.net/1969.1/86877 (accessed on 1 March 2022).
2. Ortiz, J.N.; Tarjuelo, J.M.; de Juan, J.A. Characterisation of evaporation and drift losses with centre pivots. *Agric. Water Manag.* **2019**, *96*, 1541–1546. [CrossRef]
3. Tarjuelo, J.M.; Montero, J.; Honrubia, F.T.; Ortiz, J.J.; Ortega, J.F. Analysis of uniformity of sprinkle irrigation in a semi-arid area. *Agric. Water Manag.* **1999**, *40*, 315–331. [CrossRef]
4. Saraswati, M.; Kuantama, E.; Mardjoko, P. Design and Construction of Water Level Measurement System Accessible Through SMS. In Proceedings of the 2012 Sixth UKSim/AMSS European Symposium on Computer Modeling and Simulation, Valetta, Malta, 14–16 November 2012; pp. 48–53. Available online: https://ieeexplore.ieee.org/abstract/document/6410127 (accessed on 1 March 2022).
5. Mensah, E. Economic Evaluation of Silage Crops under Reduced Irrigation in the Texas High Plains. Ph.D. Thesis, West Texas A&M University, College Station, TX, USA, 20 June 2016.
6. Roy, V.; Noureen, S.S.; Bayne, S.; Bilbao, A.; Giesselmann, M. A Renewable Solution Approach for Center Pivot Irrigation System. In Proceedings of the 2018 IEEE Rural Electric Power Conference (REPC), Memphis, TN, USA, 6–8 May 2018; pp. 61–66.

7. Lamm, F.R.; Porter, D.O.; Bordovsky, J.P.; Evett, S.R.; O'Shaughnessy, S.A.; Stone, K.C.; Kranz, W.L.; Rogers, D.H.; Colaizzi, P.D. Targeted, Precision Irrigation for Moving Platforms: Selected Papers from a Center Pivot Technology Transfer Effort. *Trans. ASABE* **2019**, *62*, 1409–1415. [CrossRef]
8. Hall, K.D.; Lacewell, R.D.; Lyle, W.M. *Yield and Economic Implications of Alternative Irrigation Distribution Systems: Texas High Plains*; Report 88-1; Tree Species; Texas Agric. Experiment Station Tech.: Lubbock, TX, USA, 1988.
9. Bosch, D.J.; Powell, N.L.; Wright, F.S. An economic comparison of subsurface microirrigation with center pivot sprinkler irrigation. *J. Prod. Agric.* **1992**, *5*, 431–437. [CrossRef]
10. Styles, S.; Bernasconi, P. *Demonstration of Emerging Irrigation Technologies*; Agreem. B56936; California Department of Water Resources: Sacramento, CA, USA, 1994.
11. Johnson, G.C.; Rochester, E.W.; Hatch, L.U.; Curtis, L.M.; Yoo, K.H. Analysis of center pivot irrigation systems operating in a humid-area environment. *Trans. ASAE* **1987**, *30*, 1720–1725. [CrossRef]
12. Dhuyvetter, K.C.; Lamm, F.R.; Rogers, D.H. Subsurface Drip Irrigation for Field Corn: An Economic Analysis; Kansas State University Cooperative Extension Service: 1994. Available online: https://agris.fao.org/agris-search/search.do?recordID=US9605677 (accessed on 1 March 2022).
13. Dhuyvetter, K.C.; Lamm, F.R.; Rogers, D.H. An Economic Comparison of Subsurface Drip Irrigation (SDI) and Center Pivot Irrigation for Field Corn. In Proceedings of the Central Plains Irrigation Short Course, Garden City, KS, USA, 7–8 February 1995; pp. 7–8.
14. Al-agele, H.A.; Nackley, L.; Higgins, C.W. A pathway for sustainable agriculture. *Sustainability* **2021**, *13*, 4328. [CrossRef]
15. AL-agele, H.A.; Nackley, L.; Higgins, C.W. Testing Novel New Drip Emitter with Variable Diameters for a Variable Rate Drip Irrigation. *Agriculture* **2021**, *11*, 87. [CrossRef]
16. Barbosa, B.D.S.; Colombo, A.; de Souza, J.G.N.; Baptista, V.B.d.; Araújo, A. Energy efficiency of a center pivot irrigation system. *Eng. Agríc.* **2018**, *38*, 284–292. [CrossRef]
17. AL-agele, H.A.; Higgins, C.W. A Variable Rate Drip Irrigation Prototype for Precision Irrigation. *Precis. Agric.* **2021**, *11*, 2493. [CrossRef]
18. AL-agele, H.A.; Proctor, K.; Murthy, G.; Higgins, C.W. A Case Study of Tomato (Solanum lycopersicon var. Legend) Production and Water Productivity in Agrivoltaic Systems. *Sustainability* **2021**, *13*, 2850. [CrossRef]
19. Al-agele, H.A.; Mahapatra, D.M.; Prestwich, C.; Higgins, C.W. Dynamic Adjustment of Center Pivot Nozzle Height: An Evaluation of Center Pivot Water Application Pattern and the Coefficient of Uniformity. *Appl. Eng. Agric.* **2020**, *36*, 647–656. [CrossRef]
20. Al-agele, H.A.; Jashami, H.; Higgins, C.W. Evaluation of novel ultrasonic sensor actuated nozzle in center pivot irrigation systems. *Agric. Water Manag.* **2022**, *262*, 107436. [CrossRef]
21. Arduino, S.A. *Arduino*; Arduino LLC: Somerville, MA, USA, 2015; p. 372.
22. Wichelns, D. Agricultural Water Pricing: United States. 2010, pp. 1–27. Available online: https://www.oecd-ilibrary.org/agriculture-and-food/sustainable-management-of-water-resources-in-agriculture/agricultural-water-pricing_9789264083578-16-en (accessed on 1 March 2022).
23. Gollehon, N.; Quinby, W. Irrigation in the American West: Area, water and economic activity. *Int. J. Water Resour. Dev.* **2000**, *16*, 187–195. [CrossRef]
24. O'brien, D.M.; Lamm, F.R.; Stone, L.R.; Rogers, D.H. Corn yields and profitability for low–capacity irrigation systems. *Appl. Eng. Agric.* **2021**, *17*, 315.
25. Molle, B.; Tomas, S.; Hendawi, M.; Granier, J. Evaporation and wind drift losses during sprinkler irrigation influenced by droplet size distribution. *Irrig. Drain.* **2012**, *61*, 240–250. [CrossRef]
26. D'Odorico, P.; Chiarelli, D.D.; Rosa, L.; Bini, A.; Zilberman, D.; Rulli, M.C. The global value of water in agriculture. *Proc. Natl. Acad. Sci. USA* **2020**, *117*, 21985–21993. [CrossRef] [PubMed]
27. Pérez, L.; Sánchez-Román, R.M.; Frizzone, J.A. Optimal moment to change pressure regulator and sprayer kit on center pivot irrigation machines: Application to a study case. *IRRIGA* **2011**, *16*, 450–458.
28. Valipour, M.; Bateni, S.M.; Gholami Sefidkouhi, M.A.; Raeini-Sarjaz, M.; Singh, V.P. Complexity of forces driving trend of reference evapotranspiration and signals of climate change. *Atmosphere* **2020**, *11*, 1081. [CrossRef]
29. Gurara, M.A.; Jilo, N.B.; Tolche, A.D. Impact of climate change on potential evapotranspiration and crop water requirement in Upper Wabe Bridge watershed, Wabe Shebele River Basin, Ethiopia. *J. Afr. Earth Sci.* **2021**, *180*, 104223. [CrossRef]